

EVALUATION OF SOLAR CELLS FOR POTENTIAL SPACE SATELLITE POWER APPLICATIONS

report to

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TABLE OF CONTENTS

	Page
List of Figures	v
List of Tables	vi
 I. SUMMARY	 1
A. PURPOSE AND SCOPE	1
B. CONCLUSIONS	2
1. Performance and Availability	2
2. Manufacturing Methods	2
3. Manufacturing Uncertainties	2
4. Effects of Concentration Ratios	2
5. Effects of the Radiation Environment	3
6. Manufacturing in Space	3
C. RECOMMENDATIONS	3
 II. BACKGROUND	 5
 III. PHOTOVOLTAIC MATERIALS	 7
A. CANDIDATES FOR SOLAR CELLS	7
B. FEDERAL PHOTOVOLTAIC CONVERSION PROGRAMS	9
C. SSP SOLAR ENERGY CONVERSION SYSTEM REQUIREMENTS	10
D. AVAILABILITY OF MATERIALS	11
 IV. SOLAR CELL MANUFACTURING METHODS	 14
A. SILICON	14
1. Single-Crystal Silicon Ribbons	15
2. Silicon Sheet	17
B. AMORPHOUS SILICON	18
C. GALLIUM ARSENIDE	19
1. Liquid-Phase Epitaxy	21
2. Vapor-Phase Epitaxy	21
3. Peeled-Film Technology	21
D. CADMIUM SULFIDE	22
1. Vacuum Deposition	22
2. Chemical Spray Deposition	22
E. IMPLICATIONS OF LARGE PRODUCTION VOLUMES	25

TABLE OF CONTENTS (Continued)

	Page
V. HIGH-VOLUME MANUFACTURE OF SOLAR CELLS	27
A. CELL PARAMETERS	27
1. High Yield	27
2. Uniformity of Cells	27
3. Low Energy Consumption	27
4. High Packing Factor	29
B. MANUFACTURING UNCERTAINTIES	29
C. COSTS	30
1. Projection Methods	30
2. Solar Cell Cost Projections	33
VI. EFFECTS OF CONCENTRATION RATIO	35
VII. EFFECTS OF SPACE ENVIRONMENT	40
VIII. SPACE MANUFACTURE OF SOLAR CELLS	44
REFERENCES	48

LIST OF FIGURES

Figure No.		Page
1	SSP Design with Photovoltaic Conversion	6
2	Theoretical Efficiency of Photovoltaic Materials	7
3	Expansion of Output of Metallurgical-Grade Silicon	16
4	GaAs Solar Cell	21
5	Historical and Projected CdS Thin-Film Efficiency Improvement	23
6	CdS Solar Cell Produced by Chemical Spray Technique	24
7	Terrestrial Solar Array Price Goals	28
8	Reduction Projections Based on Industry Experience	32
9	Variation in Array Mass of SSP as a Function of Concentration Ratio – Silicon	36
10	Variation in Array Mass of SSP as a Function of Concentration Ratio – Cadmium Sulfide	37
11	Variation in Array Mass of SSP as a Function of Concentration Ratio – Gallium Arsenide	38
12	Radiation Environment During Minimum Time Transfer Orbit from LEO to GEO	43
13	Cost of Transporting Polycrystalline Silicon to LEO Compared With Terrestrial Production Costs of Polycrystalline Silicon	46

LIST OF TABLES

Table No.		Page
1	Summary of Typical Properties of Candidate Photovoltaic Materials	8
2	Theoretical Conversion Efficiencies (AMO) 26° C For Alternative Heterojunction Materials	9
3	Availability of Alternative Cell Materials	12
4	Availability of Gallium	13
5	Process Steps in Fabrication of Single Crystal Silicon Solar Array	15
6	Solar Cell Array Production Rate Requirements	25
7	Required Linear Manufacturing Rates of Solar Cell Array	26
8	SSP Area Required for Specific Solar Cell Efficiency	26
9	Comparison of Total Energy Requirements to Produce Silicon and Other Common Metals	29
10	Definition of Regions of Geomagnetically Trapped Electrons and Protons	40
11	Summary of Periods of Solar Cycles	41
12	Options I-III for Fabrication and Assembly of Single-Crystal Silicon Solar Arrays for SSP	45
13	Option IV for Fabrication and Assembly of Single-Crystal Silicon Solar Arrays for SSP	45

EVALUATION OF SOLAR CELLS FOR POTENTIAL SPACE SATELLITE POWER APPLICATIONS

I. SUMMARY

A. PURPOSE AND SCOPE

Feasibility studies of space satellite power (SSP) have indicated that solar energy conversion by the photovoltaic process is a promising approach. Under contract NAS 9-15294, Arthur D. Little, Inc., was authorized by the NASA Lyndon B. Johnson Space Center, Houston, Texas, to evaluate various solar cell materials and manufacturing methods and to identify options which show the greatest promise of leading to the development of a cost-effective SSP design. This evaluation, which extended over the time period from March 7, 1977 to May 31, 1977, focussed on the following issues:

- The relative merits of alternative solar cell materials, based on performance and availability;
- The best manufacturing methods for various solar cell options and the effects of extremely large production volumes on their ultimate costs and operational characteristics,
- The areas of uncertainty in achieving large solar cell production volumes;
- The effects of concentration ratios on solar array mass and system performance;
- The factors influencing solar cell life in the radiation environment during transport to and in geosynchronous orbit, and
- The merits of conducting solar cell manufacturing operations in space.

Our evaluation was based on published data and on information obtained from photovoltaic specialists at NASA, JPL, ERDA, WPAFB, academic institutions and industrial laboratories. The available information was used in conjunction with the results of ongoing SSP systems studies to project future directions for solar cell development applicable to the SSP.

B. CONCLUSIONS

1. Performance and Availability

Single-crystal silicon continues to be the leading candidate for SSP solar cell arrays because of significant production experience and an extensive data base. However, amorphous silicon could be a more attractive material if development goals can be met.

Silicon is the most available photovoltaic material. Cadmium is a less available alternative material. Gallium availability, however, may be limited unless low-cost processes to extract gallium from potential sources such as bauxite, fly ash, and oil residues are developed

2. Manufacturing Methods

Several manufacturing methods show promise for meeting the large-scale production requirements of SSP solar cell arrays: i.e., web dendritic growth of single-crystal silicon; discharge-produced amorphous silicon, and deposition techniques for cadmium sulfide

The extremely large production volumes required to meet projected SSP deployment schedules will have a significant impact on several industry sectors which would contribute to solar cell manufacturing. Therefore, sufficient lead times will be necessary to build up industry capacity to mine and process photovoltaic materials, to produce, package and deliver solar cell arrays to spaceports.

Cost projections indicate that with increasing production volumes to meet expanding markets, cost goals of the SSP solar cell arrays could be met if uncertainties associated with achieving required production volumes could be overcome through further solar cell technology developments

The production capacity required to support pilot and prototype SSP demonstrations could be designed to be shared between SSP and terrestrial solar cell applications so as to assure that continuous output, large production volume facilities could be justified.

3. Manufacturing Uncertainties

The main uncertainties associated with achieving large production volumes lie in the ability to develop (1) production methods that can rapidly produce the quantities of solar cells required, (2) the concomitant production controls to achieve predictable cell performance, (3) material processes and production methods that are much less expensive than those now available, and (4) the required capital investment resources

4. Effects of Concentration Ratios

Low concentrations of solar cells, up to a ratio of 2.4, would help to reduce the mass of silicon and cadmium sulfide solar cell arrays; however, any concentration would necessitate additional supporting structures for the solar reflectors. In addition

to introducing system complexities, the reflecting mirror surfaces are subject to degradation in the space environment. Thus systems with continuous thin-film silicon or cadmium sulfide solar cell arrays without concentration would be simpler to construct and maintain.

Gallium arsenide solar cells in higher concentration ratios would reduce the total array mass. But solar reflectors with high concentration ratios require more complex support structures and more precise pointing and attitude controls.

5. Effects of the Radiation Environment

Single-crystal silicon solar cells would be subject to substantial degradation during passage through the Van Allen belts; therefore, they will require protection. In geosynchronous orbit the protective covers for amorphous silicon and cadmium sulfide thin-film cells need not be as thick as those for single-crystal silicon.

6. Manufacturing in Space

Space manufacture of solar cells is of interest if single-crystal silicon solar arrays are to be used for the SSP. The decision to manufacture in space would partially depend on the mass of protective material required to provide adequate shielding for single-crystal silicon solar cells during passage through the Van Allen belts if ion propulsion were used. Chemical propulsion would reduce the mass of protective material required because of the shorter transit time through the belts. Space manufacture of solar cells has not yet been shown to be technically feasible or economically promising as an alternative to transporting silicon solar cells from the Earth. However, development of space manufacture of solar cells would open up a future option to produce silicon solar cells from lunar surface materials. Furthermore, it could also permit the recycling of silicon solar cells should annealing procedures fail to restore performance to the desired high level.

C. RECOMMENDATIONS

The ERDA National Photovoltaic Conversion program, although furthering the photovoltaic materials and solar cell production technology, will not meet all of the SSP solar cell array development objectives. Valuable information and experimental data are being obtained and are useful for the SSP system and economic studies. However, the goals of the SSP solar cell array development are sufficiently different from terrestrial solar cell requirements so that a dedicated photovoltaic conversion program will be required.

Substantial cost savings could be achieved if solar cell materials and designs were developed to meet both SSP and terrestrial solar cell requirements. Therefore, we recommend that the following tasks be included in the SSP development program:

(1) Perform R&D on candidate solar cells for SSP to achieve:

- Low mass per unit area,
- High efficiency,
- High radiation resistance,

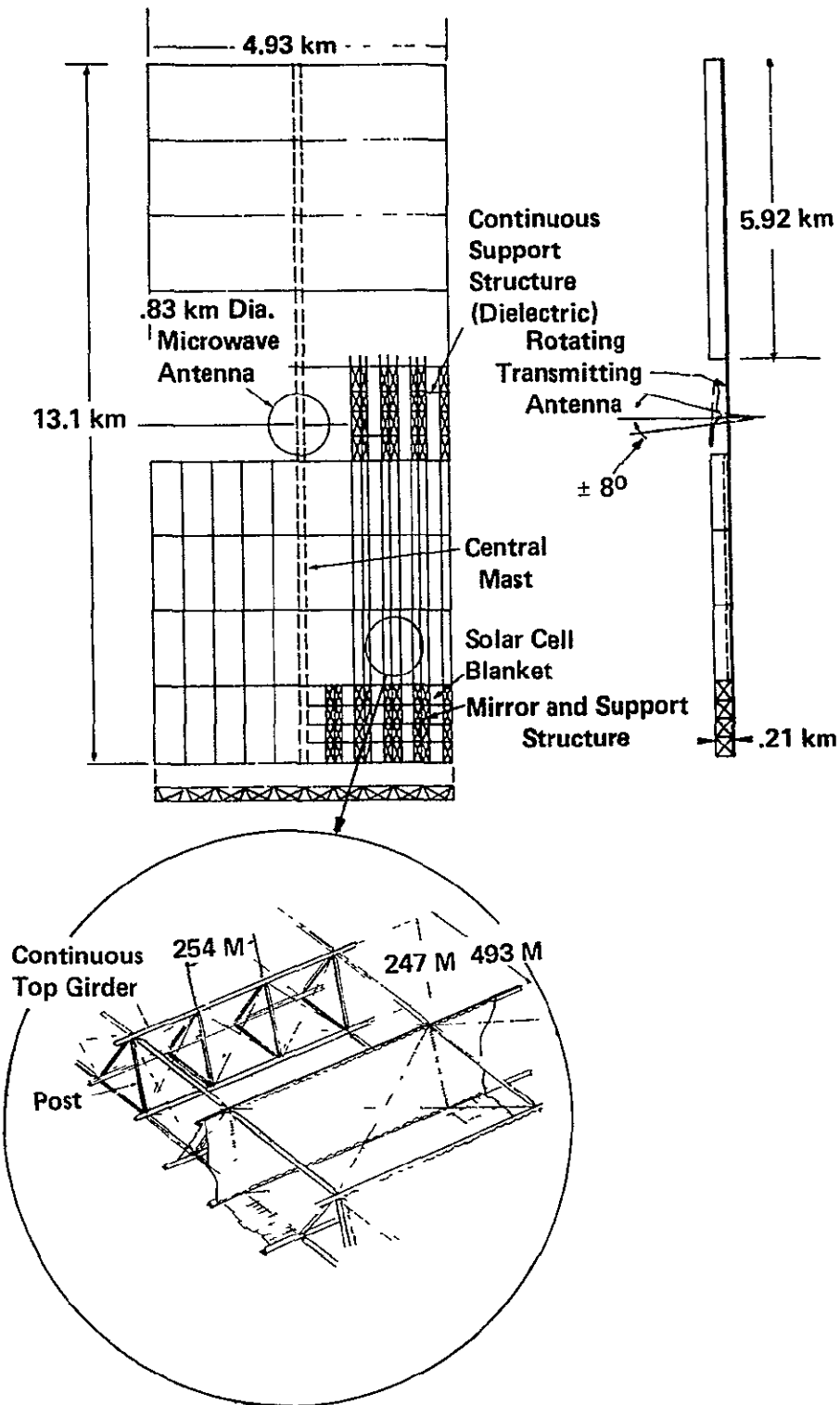
- Capability of being packaged for subsequent deployment and assembly in orbit,
 - Capability of integration with extended lightweight structures, and
 - Capability of approaching initial performance with suitable processing (e.g., annealing) after prolonged exposure to the space environment
- (2) Monitor on-going terrestrial cell material development programs and select for in-depth evaluation and development those materials which are most promising for SSP.
 - (3) Develop solar cell materials and designs which could meet SSP requirements while also benefiting terrestrial applications
 - (4) Establish an on-going orbital test program for flight testing of candidate solar cells, solar cell arrays, and structure-array integration methods as piggyback experiments on planned and future spacecraft, on LDEF, and on shuttle/spacelab missions
 - (5) Establish an orbital program for flight testing of candidate solar cell arrays and assembly methods on a SSP module scale.

II. BACKGROUND

As originally conceived, an SSP can utilize any of several current approaches to solar energy conversion — photovoltaic, thermoelectric, thermionic — and others likely to be developed in the future. Among these conversion processes, photovoltaic conversion is a good starting point because solar cells already are in wide use in satellites. Currently, photovoltaic materials being considered for SSP applications include single-crystal silicon solar cells and gallium arsenide solar cells.

Figure 1 shows an SSP design concept, based on photovoltaic conversion, which embodies many of the generic design features of other photovoltaic SSP design concepts which are being evaluated as part of ongoing systems studies.¹ The two rectangular solar cell arrays, each about 6 kilometers long and 5 kilometers wide, indicate the large area required for the SSP and the challenges that this implies for producing appropriate solar cell arrays, their support structures and assembly procedures. The radiation effects of the Van Allen belts on the solar cell arrays during their transit to geosynchronous orbit could accelerate the degradation of the solar cells' performance in the space environment. Therefore, important system considerations are the choice of photovoltaic materials for the solar cells, their protection from the space environment, their restoration to initial performance by *in situ* annealing processes, and subsequent augmentation with additional solar cell arrays to maintain required power output. Other important considerations are the effects of micrometeoroid impacts on and prolonged exposure to the space environment of solar reflectors which may be used in conjunction with the solar cell arrays

The solar energy conversion system represents nearly 70% of the SSP mass. Because the solar cell arrays are the major contributors to the mass, the choice of photovoltaic material, the solar cell performance and assembly methods will have the most significant influence on the cost of SSP-supplied power. Thus, solar cells for SSP application merit detailed evaluation



Source: Arthur D. Little, Inc., Grumman Aerospace Corporation, Raytheon Company, Spectrolab, Inc.

FIGURE 1 SSP DESIGN WITH PHOTOVOLTAIC CONVERSION

III. PHOTOVOLTAIC MATERIALS

A. CANDIDATES FOR SOLAR CELLS

Since the development of solar cells by Bell Telephone Laboratories in the early 1950's, the solid-state physics underlying the photovoltaic conversion process has been developed so that the theoretical performance of photovoltaic materials can be predicted with reasonable confidence. Single-crystal silicon, one of the most useful materials in the electronics industry, is by far the most developed photovoltaic material (Figure 2). Thus, single-crystal silicon and the solar cells produced from it have had the benefit of substantial production development over the past 25 years, by comparison, the state of the art of other candidate materials lags far behind. Furthermore, the ERDA/JPL Photovoltaic Conversion Program is focussed on silicon solar cells, its objective being to develop low-cost, reliable photovoltaic systems and to stimulate the creation of a viable industrial and commercial capability to achieve the projected production volumes at predictable and reasonable costs. The primary focus of this program, however, is on terrestrial applications of solar cells for widespread use in residential, commercial, and governmental applications.

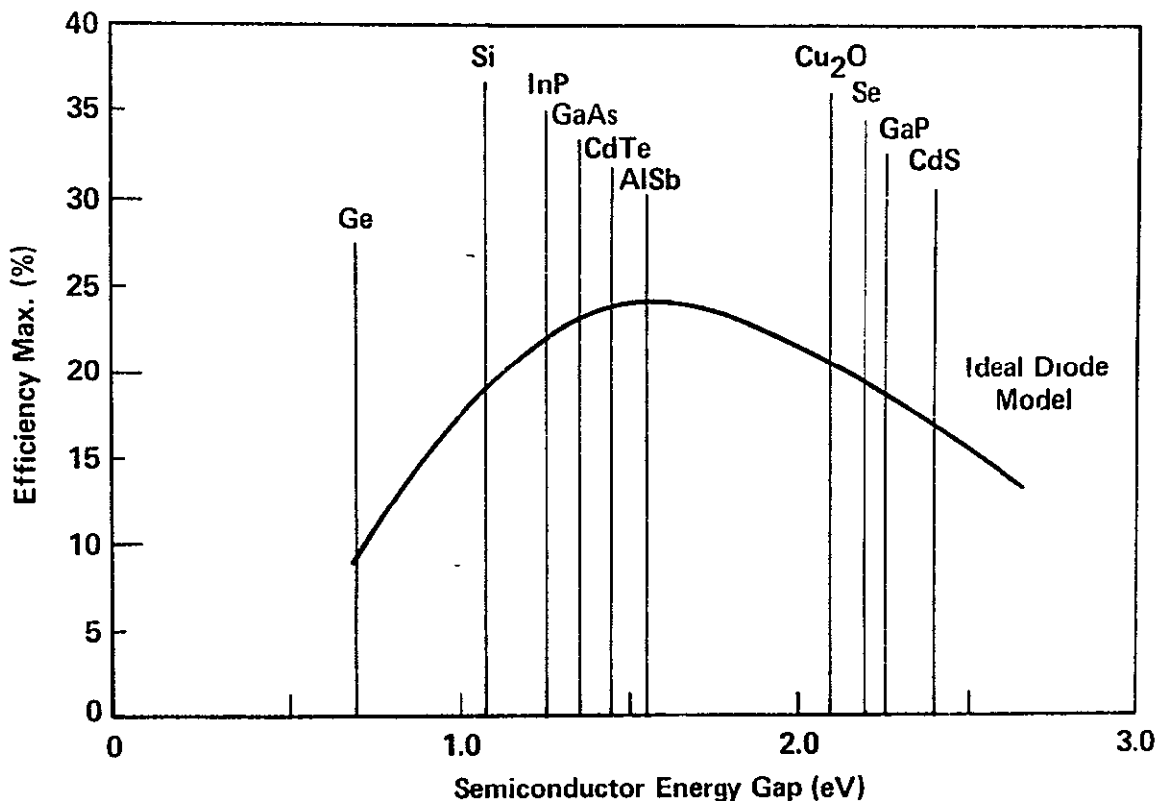


FIGURE 2 THEORETICAL EFFICIENCY OF PHOTOVOLTAIC MATERIALS

In addition to silicon, among the candidate photovoltaic materials (Table 1), cadmium sulfide represents an interesting possibility because it has the potential for mass production in the form of polycrystalline thin-film solar cells. Gallium arsenide is also of interest because it can be produced in thin-film form and because it can be used in high concentrations with only limited loss in performance.

TABLE 1
SUMMARY OF TYPICAL PROPERTIES OF CANDIDATE PHOTOVOLTAIC MATERIALS

Material	η	η	Array Thickness (μm)	Mass (g/cm^2)	Nominal Cost	
	Theoretical (%)	Actual (%)			$\$/\text{m}^2$	$\$/\text{W}$
Silicon	22	12	510	115	87	.5
Gallium Arsenide	26.5	14	191	.0432	203	1.1
Cadmium Sulfide	17.6	8	76	0.149	87	.8
Indium Phosphorus	23.5	12.5	81	.0155	—	—
Cadmium Telluride	27.0	—	~ 81	0.155	—	—

All efficiencies are at 26°C, AMO, No Concentration, BOL.

Source: Arthur D. Little, Inc., estimates.

Zinc phosphide, only recently being evaluated (at the University of Delaware), is a potential thin-film solar cell material. Its performance is projected to be equivalent to that of cadmium sulfide and it does not have the cadmium and gallium drawback of limited availability. It is highly likely that through the expanded research efforts under the ERDA Photovoltaic Conversion Program, the performance of alternative heterojunction photovoltaic materials will be improved (Table 2).

In addition, there are alternative methods for preparing silicon solar cells; for example, the multiple-junction edge-illuminated solar cell,² which is designed for high-voltage and low-current applications and can be operated at high concentration factors, the vertical-junction solar cell,³ whose radiation resistance is expected to be better than that of other silicon solar-cell constructions, and the interdigitated silicon solar cell being developed by Texas Instruments, where a series of interdigitated p+ and n+ contacts are placed on the unilluminated side of the solar cell. These silicon cell constructions merit further study for possible application to the SSP.

TABLE 2
THEORETICAL CONVERSION EFFICIENCIES
(AMO) 26°C FOR
ALTERNATIVE HETEROJUNCTION MATERIALS

<u>Junction Materials</u>		Efficiency (%)
P	n	
ZnTe	/ CdSe	6
ZnTe	/ CdTe	14
CdTe	/ CdS	17
CdTe	/ ZnSe	21
CdTe	/ ZnCdS	23
Cu ₂ S	/ CdS	10
Cu ₂ S	/ ZnCdS	15
Ge	/ GaAs	14
GaAs	/ ZnSe	19
InP	/ CdS	20

Because the current solar cell technology is based on single-crystal silicon, there is a large difference in the level of established technology compared to other candidate photovoltaic materials. Alternative photovoltaic materials, particularly those which could be of interest to the SSP, are in an early stage of technology development. Even the single-crystal silicon solar cell, however, can benefit from additional research efforts toward achieving its theoretical performance efficiency, as, for example, in the current studies on the effects of impurities on performance.

B. FEDERAL PHOTOVOLTAIC CONVERSION PROGRAMS

Both ERDA and DOD have ongoing photovoltaic conversion programs. The objectives of the ERDA Photovoltaic Conversion Program are as follows:⁴

- Reduction by 1986 of silicon solar array prices by a factor of 30 to \$500 per peak kilowatt, with an annual production of 500 MW per year,
- Development by 1986 of photovoltaic solar cell and solar concentrator systems capable of producing power at \$250 per peak kilowatt,
- Reduction by the year 2000 of solar array prices by a factor of 100 or greater by focussing R&D on novel materials and devices;
- Achievement by the year 2000 of a production volume of 5000 MW per year of solar array modules at a market price of \$100 to \$300 per peak kilowatt, and
- Achievement by the year 2000 of the photovoltaic solar cell industry's technological capability to provide 3% of the U S electrical power demand.

The objectives of the Department of Defense Photovoltaic Conversion Program are as follows:

- Achievement of high efficiencies for solar cells so that additional power can be provided for operational spacecraft without major redesign, and
- Achievement of increased radiation resistance so that the lifetime of an operational spacecraft can be extended, thus necessitating fewer launches.

Although both the ERDA and DOD Photovoltaic Conversion Programs help to support the development of SSP solar cell technology, achievement of their program objectives is unlikely to satisfy the specific requirements of the SSP solar energy conversion system.

C. SSP SOLAR ENERGY CONVERSION SYSTEM REQUIREMENTS

The power generated by the SSP at the receiving antenna on Earth will be in the range from 2,000 to 15,000 megawatts. At a nominal power output of 5,000 MW, the solar energy conversion system will have to generate about 9,000 MW to allow for conversion and microwave generation, transmission, and rectification inefficiencies. A production scenario of 112 SSP's placed in operation by 2025^s would require the deployment of up to 7 SSP's per year. Assuming that commercial operations were to start by 1996, by the year 2000 the SSP production capability would be about 50 thousand MW per year, which is about 10 times the annual output projected for the ERDA Photovoltaic Conversion Program.

Solar cell arrays for the SSP must meet the following requirements

- High efficiency,
- Low mass per unit area,
- Low cost per watt per unit area,
- Radiation resistance during operation in geosynchronous orbit and in transit to this orbit,
- Production rates consistent with SSP deployment schedules,
- Integration with transportation and SSP system requirements, and
- Adequate materials to meet projected production volumes

Therefore, it is likely that the development effort for the SSP solar cell arrays will have to include not only single-crystal silicon but also the following photovoltaic materials:

- Amorphous silicon,
- Cadmium sulfide, and
- Gallium arsenide.

The requirements for low cost per watt per unit area of the SSP solar cell array also make it likely that the choice of photovoltaic material will be strongly influenced by the capability to extract the selected materials from mineral resources at low cost.

This requirement is what distinguishes the objectives of the SSP solar cell array development program from those of the DOD development program, where the stress is primarily on high efficiency and radiation-resistant solar cells.

Solar concentrators could significantly reduce the material and solar cell production requirements. However, they would add complexity, in the form of more precise optical components and pointing and attitude controls and more difficult orbital assembly procedures.

The higher the solar cell efficiencies the smaller the SSP solar cell array area, and therefore, the less the production rate. However, high-efficiency solar cells may be subject to more degradation than lower efficiency cells during prolonged exposure to the space environment, thus requiring a thicker protective cover and increasing the mass of the solar cell array. Although gallium arsenide solar cells have been shown to be more resistant to radiation than conventional and "violet" silicon solar cells, a cover will be required to protect even the more resistant solar cells from the effects of the space environment.

Production of solar cells with consistently high efficiency will necessitate tight production and quality controls which generally can be economically justified only at large production volumes. Photovoltaic materials such as amorphous silicon, cadmium sulfide, and gallium arsenide will require further development to achieve projected solar cell efficiencies when mass produced.

The economics of terrestrial solar cells are usually based on the cost per peak watt. In the SSP, however, there is the additional consideration of the area of the solar cell array (i.e., cost per watt per unit area), the array and supporting structure mass, and the concomitant transportation and assembly costs. Thus, the cost per watt per unit area is one — but not the primary — important input to economic analyses to determine the cost of SSP-supplied power.

D. AVAILABILITY OF MATERIALS

In principle, a large number of photovoltaic materials deserve careful evaluation because of either their performance or their low cost. However, the choice of photovoltaic materials for the SSP should be guided not just by the technical considerations but also the effects on world supply of mineral resources, the market impacts of by-products which may be produced in extracting the photovoltaic materials and the environmental implications of the mining and processing of large quantities of mineral resources. Furthermore, the reserves of mineral resources available within the United States are limited; therefore, the choice of photovoltaic materials should also be guided by the impact importing mineral resources would have on trade balances.

Table 3 shows the availability of alternative cell materials based upon the assumptions that each SSP will require a solar energy conversion system using 5- μ m-thick solar cells operating at 12% efficiency with a solar constant of 1353 W/m², without concentration, to generate 10,000 MW. Commercial availability of materials (Table 3) favors the use of silicon as the photovoltaic material. Cadmium may be considered a candidate photovoltaic material, however, its production would be at a rate far in excess of present market needs and could lead to major dislocations in the

world zinc market. Although production of cadmium could be expanded to meet SSP requirements, mineral resources outside the United States probably would have to be made available and a new market structure for zinc established. Thus the economic desirability of a greatly expanded supply of cadmium is questionable. The supply of gallium to meet SSP requirements would severely strain world bauxite reserves. Gallium, however, is available from other sources (Table 4). A process for extracting gallium from fly ash is under development in France. Should it be possible to develop an economical process, up to 8,000 metric tons of gallium could be produced from fly ash each year to meet SSP requirements, assuming that coal would be a major source for fly ash and that fly ash in the required and assured quantities would be available for the processing plants. The process and the infrastructure required to support it with coal-derived fly ash will require substantial development. The concentration of gallium in sea water is so low (3×10^{-6} mg per liter) that 3.3×10^{10} liters would have to be processed to obtain one kilogram of gallium, assuming 100% recovery. Dedicated pumping costs alone would be about \$7,000 per kilogram of gallium, even if a suitable process (for example, one based on ion exchange) were developed.

TABLE 3

AVAILABILITY OF ALTERNATIVE CELL MATERIALS

(Assuming 5 GW of Space Satellite Power (10 GW Generated) Using 5- μ m-Thick Solar Cells Operating at 12% Efficiency With a Solar Constant of 1353 W/m² and No Concentration)

Cell Type	Material	Remarks
Si	Silicon	No Practical Limit Imposed By Availability
CdS	Cadmium	1 Satellite Requires 50% of Total U.S. Production; Supply Would be Very Difficult
In ₂ O ₃	Indium	1 Satellite Would Require More Than the Total Known World Reserves
GaAs	Gallium	100 Satellites Would Require 75% of All Known Bauxite Reserves Be Mined; if Gallium Were Recovered From All Bauxite Mined Today — Only 1/3 of 1 Satellite
SnO ₂	Tin	No Practical Limit Imposed By Availability
ZnP	Zinc	No Practical Limit Imposed By Availability
Al	Aluminum	No Practical Limit Imposed By Availability
CdS/Cu ₂ O	Copper	No Practical Limit Imposed By Availability
CdS	Sulfur	No Practical Limit Imposed By Availability
CdTe	Tellurium	1 Satellite Requires 5 Times as Much Tellurium as Total World Production, Total Known Reserves Sufficient for Less Than 50 Units
Sb ₂ O ₅	Antimony	1 Satellite Requires 10% U.S. Production, Probably Could Be Accommodated
ZnP	Phosphorus	No Practical Limit Imposed By Availability

TABLE 4
AVAILABILITY OF GALLIUM

Source	Amount
Bauxite	100 PPM
Zinc Sulfide	50 PPM
Fly Ash	50-100 PPM
Seawater	3.0×10^{-5} mg/liter

Note: Estimated 1976 U.S. Production
2 MT as Aluminum and Zinc By-
Product One SSP Could Utilize
900 MT With No Concentration

On the basis of material availability, therefore, cadmium and gallium cannot be excluded as candidate photovoltaic materials for the SSP. However, assuming equivalent performance and cost, thin-film materials based on the use of zinc represent a very attractive development option.

Among other materials required for the SSP solar cell array are the protective cover and the substrate and reflecting optics. The protective cover could be made from available materials such as glass resin developed by Owens-Illinois, sprayed FEP developed by Lockheed, or heat-laminated FEP developed by TRW.⁶ The glass resin and FEP are used in 10- μ m thicknesses. Kapton is the candidate material for the substrate for the solar cell array and for the reflecting optics. An SSP with a solar cell array area of 50 square kilometers (no concentration) would require 3.6×10^6 kg of Kapton, assuming that 25- μ m Kapton could be used for the substrate.

Kapton film production — the total for 1976 was about 0.3×10^6 kg — is increasing at a rate of about 1.5% per year. The 1976 price of Kapton for one SSP was about \$120 million. Kapton uses petroleum resources; therefore, the price may rise as petroleum supplies diminish. The Kapton thickness for the substrate could be reduced, but 12.5- μ m-thick films are twice as expensive per unit as 25- μ m-thick films, although this price differential could be decreased if production equipment dedicated to producing thin Kapton films were available.

IV. SOLAR CELL MANUFACTURING METHODS

A. SILICON

The major effort under the ERDA Photovoltaic Conversion Program is devoted to the development of low-cost silicon solar array technologies. The objectives are to achieve an efficiency greater than 10%, an operating lifetime greater than 20 years and solar cell arrays at a price of less than \$500 per peak kilowatt by 1986. The following aspects are being investigated:

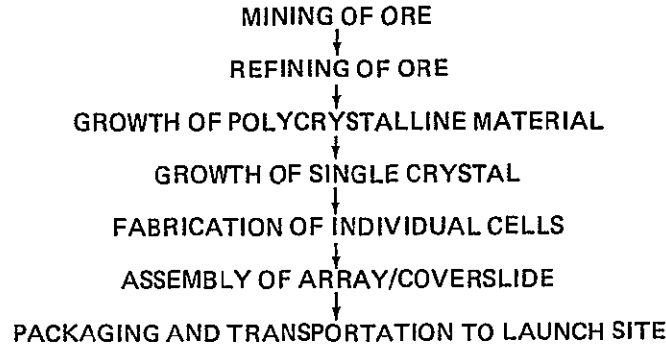
- Silicon materials,
- Large-area silicon sheets,
- Encapsulation methods, and
- Automated assembly of arrays.

In addition, two solar cell arrays, one in 1977 with an output of 40 kW, and the other in 1978 with an output of 130 kW, are being procured to test and demonstrate performance specifications and environmental requirements of the ERDA photovoltaic system.

Major efforts are being devoted to the growth of single-crystal silicon and the fabrication of individual cells, several of the other process steps (Table 5) still require definition. For example, the refining of ores and the preparation of metallurgical-grade silicon as a starting material for solar cell production will require a substantial expansion of output (Figure 3). The production of both semiconductor-grade silicon and solar-cell-grade silicon is being investigated to develop significantly less-expensive silicon refining processes. For example, the production of silicon from SiCl_4 by the reduction of zinc in a fluidized-bed reactor being developed by Battelle Memorial Institute is projected to reduce costs from the present \$65/kg of semiconductor grade silicon to about \$10/kg. Union Carbide is investigating the possibility of reducing the cost of producing SiH_4 to \$3-5/kg by redistributing a mixture of chlorinated silanes to yield SiH_4 . Monsanto and Westinghouse are investigating the effects of impurities on solar cell performance to establish permissible impurity concentrations. For example, titanium, vanadium, and aluminum can cause severe degradation, whereas carbon impurities seem to improve the efficiency of solar cells produced from Czochralski-grown single-crystal silicon. The performance of float-zone-prepared solar cells containing carbon is slightly degraded. Finally, Dow Corning is investigating processes for producing solar-cell-grade silicon which could reduce silicon costs to about \$5/kg, including the reduction of SiO_2 , by using an induction plasma torch and a submerged arc furnace with subsequent unidirectional freezing and vacuum evaporation. The results of these studies and planned demonstration of promising processes are required to indicate the technical and commercial feasibility of reducing the cost of silicon by a factor of 10 below the present cost.

TABLE 5

**PROCESS STEPS IN FABRICATION OF
SINGLE CRYSTAL SILICON SOLAR ARRAY**



1. Single-Crystal Silicon Ribbons

To achieve large production rates, a number of techniques for growing single-crystal silicon suitable for solar cell production are being investigated. These include ribbon growth processes based on the following techniques:

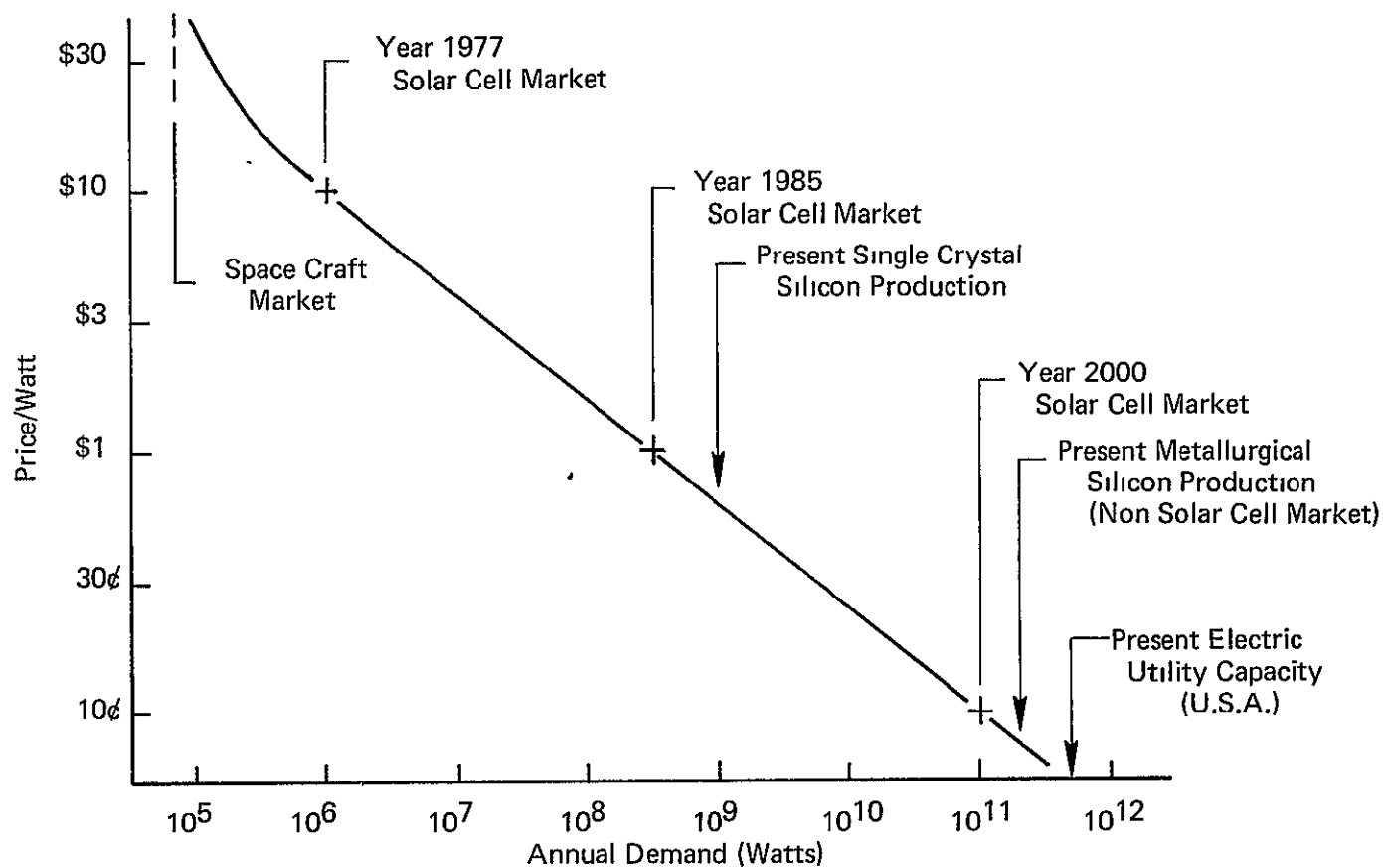
a. Edge-defined Film-fed Growth (EFG)

This growth technique, being developed by Mobil-Tyco and IBM, is based on feeding molten silicon through a slotted die. The shape of the ribbon is determined by the contact of molten silicon with the outer edge of the die. The die is constructed from material, e.g., graphite, which is wetted by the molten silicon. Growth rates of about 3 cm/min and efficiencies of 10% (AMO) have been demonstrated. The intermediate goal is a process speed of 7-1/2 cm/min and ribbons 7-1/2 cm wide. At the higher speeds, the ribbon is stressed, thus tending to fracture it during or after the growth process. The ribbons are about 200 μ m thick. At the low growth rate, meter-long ribbons have been grown. The challenge to the EFG process is the contamination of the ribbon material from the wetted die, so far, this contamination has made the material unsuitable for high-efficiency solar cells.

Assuming reasonable technology advancement, economic analysis of the EFG ribbon process indicates that this technique can achieve costs on the order of several hundred dollars per kilowatt.

b. Web-dendritic Growth

The major advantage of the web-dendritic growth process developed by Westinghouse and also being investigated at the University of South Carolina is that thin dendrites can be made to grow ahead of the silicon web being pulled from a pool of molten silicon; these dendrites support the molten silicon between them to form the ribbon. The dendrites guide the growth in a very precise orientation and, therefore, the ribbon, which grows between them, takes on a precise orientation. Furthermore, no die is required, thus the purity of the material is easier to control. The unique orientation



Source: Texas Instruments.

FIGURE 3 EXPANSION OF OUTPUT OF METALLURGICAL - GRADE SILICON

and slight undercooling to insure faster growth gives the ribbon a flat surface finish and excellent control over thickness. Solar cells grown from web-dendritic ribbon material have achieved 11% efficiency (AMO), and 16% efficiency is considered to be a reasonable goal. A thickness of 50 μm should also be achievable. The limitations to the process appear to be in achieving the maximum growth rate and width. Single-crystal dendrites at least one meter long have been grown at a rate approaching 5 cm/min, and 10 cm/min appears to be a reasonable goal.

c. Laser-zone Ribbon Growth

In this process, being developed by Motorola, a polycrystalline silicon ribbon is fed to a preheated region, which is melted by a focused laser beam and then recrystallized. The liquid silicon is held in place by its own surface tension, the shape of the crystal is defined by the shape of the feedstock and the orientation is determined by a seed of single-crystal ribbon. A growth rate of 1 cm/min. for a ribbon 1 to 2 cm wide and about 150 μm thick is considered to be achievable.

d. Inverted Stepanov Growth

Ribbon growth of single-crystal silicon, being investigated by RCA, uses a non-wetted die to minimize the reaction between the molten silicon and the die material. The introduction of the feed from above and the growth of the single crystal in a downward direction partly compensates for the hydrodynamic drag in the slot and for the lack of capillary rise. The objective is to grow ribbons about 2-½ cm wide, and 100 to 200 μm thick. Experiments have not yet successfully produced the desired ribbon growth.

2. Silicon Sheet

Several growth processes are being investigated because of their potential for large-area growth of silicon sheets on inexpensive substrates. The following are typical:

a. Dip Coating

Honeywell has produced films of silicon on ceramic substrates about 5 cm square and approximately 1 mm thick. The substrates were withdrawn from the molten silicon at rates of up to 3 cm/sec. The silicon films have ranged in thickness between 10 and 50 μm , with single-crystal grains in the film measuring up to 2 cm. Ceramics which can be selected to match the thermal expansion of silicon are coated with a film of carbon or silicon carbide to enhance the adhesion of the silicon film.

b. Chemical Vapor Deposition on Low-Cost Substrates

Rockwell International is investigating the growth of silicon sheets by reducing silicon compounds at elevated temperatures and depositing them on a suitable substrate. The goal is to produce a silicon sheet 30 cm wide at a deposition rate of 5 μm /min., with thicknesses ranging from 20 to 100 μm and a crystal structure with an average grain size of 100 μm . Silicon layers with grain sizes of about 0.9 μm have been produced and efforts are underway to enlarge grain growth.

c. Chemical Vapor Deposition on a Floating Silicon Substrate

In this process, being developed by General Electric, single-crystal silicon is formed by direct deposition from gaseous SiH_4 . SiH_4 is passed over a silicon substrate supported on a thin film of molten tin in a reactor. Single crystals grow to the desired thickness by vapor-phase epitaxy. Fresh substrate silicon is nucleated at one end of the reactor where the edge of the growing sheet is in contact with the region of the tin which is saturated with silicon. The process is continuous, the finished sheet being withdrawn from the opposite end of the growth zone. The goal is to grow single-crystal silicon with an area of 0.5 cm^2 .

d Hot Forming of Silicon

Hot rolling is being investigated by the University of Pennsylvania to produce silicon sheets $100 \mu\text{m}$ thick at a linear output rate of 3 cm/sec . Currently no known roller materials are useable at the 1380°C temperature required for this process.

e. Cast Silicon

The casting of silicon is designed to increase the grain size of polycrystalline material. The chosen substrate and carrier gas and temperature control during remelting and recrystallization have produced grain sizes exceeding one millimeter and these have been arranged so that no grain boundaries are cast perpendicular to the majority carrier current flow. When sliced into thicknesses of $350\text{--}450 \mu\text{m}$, the cast block of non-single silicon crystals has produced solar cells which consistently showed an efficiency of 10%.⁷ Although the cast slab will be cheaper to produce than single-crystal ingots, the thickness and efficiency appear to limit the potential of this material for SSP.

On the basis of the progress achieved to date in the low-cost silicon solar array project, the web-dendritic growth process appears to be the most promising to produce single-crystal silicon solar cells for the SSP. None of the silicon sheet processes has shown enough promise to be able to meet SSP solar cell array requirements.

However, all these processes will have to compete with the present single-crystal silicon growth technology which is based on the Czochralski process. This process produces excellent-quality single-crystal silicon in ingots up to 4 inches in diameter. Although it is a batch process, substantial experience has been obtained with Czochralski-grown silicon and the subsequent process steps required to produce efficient solar cells. Substantial improvements will have to occur in competing processes before they will supplant the Czochralski process. Improvements in slicing of Czochralski ingots into wafers, for example, by multiple wire and bread knife sawing, which have the potential to be scaled up for large-scale production, could also increase the rate of material slicing, while reducing slice thickness, material loss and wafer surface degradation. The goal of the ingot-cutting investigations by Crystal Systems and Varian are to achieve slicing rates of 10 mil/min and to produce 100 parallel slices from a 4-inch ingot at wafer thicknesses of $125 \mu\text{m}$ and kerf losses of $125 \mu\text{m}$.

B. AMORPHOUS SILICON

Continuous discharge-produced amorphous silicon, being developed at RCA, has been shown to be a promising new solar cell material.¹⁷ An amorphous silicon film of $1 \mu\text{m}$ thickness can absorb most of the solar radiation because the optical absorption

coefficient exceeds that of crystalline silicon by an order of magnitude over the visible light range. The photo-generated carriers can be collected using p/n or Schottky barrier structures. P/n structures exhibit poor performance because it is difficult to obtain low-defect p-doped material. An improved process or a different doping material will be required to produce more efficient p-type amorphous silicon. These devices can be fabricated with large built-in potentials (approximately 1 volt) and relatively low series resistances. The theoretical limit for the amorphous silicon solar cell has been estimated to be 15%. Conversion efficiencies as high as 5.5% have been obtained using platinum Schottky barriers and ZrO_2 anti-reflection coatings. Substrate materials such as steel, aluminum, plastic, and glass can be utilized

Amorphous silicon solar cells represent one of the most promising approaches to meeting SSP requirements for the following reasons:

- no practical limit on materials availability,
- potential for low-cost production (current projections are 10¢ per watt),
- improved radiation-resistance compared to single-crystal silicon;
- capability of being annealed at temperatures in the range of 60 to 100°C;
- low production losses;
- high potential production rates,
- potential for space manufacture; and
- choice of inexpensive substrates.

Amorphous silicon solar cells are in too early a development stage to permit definitive conclusions to be made regarding their applicability to the SSP. Furthermore, it would be desirable to develop p/n structures rather than the efficiency-limiting Schottky barrier structures. However, even at this stage of development, amorphous silicon solar cells represent one of the most important new developments for SSP applications.

C. GALLIUM ARSENIDE

There has been considerable interest in GaAs solar cells, primarily because conversion efficiencies of 17% (AMO) have been demonstrated and there is a high likelihood that 20% efficiencies are achievable.⁸ Furthermore, GaAs cells have a substantial advantage because at elevated temperatures their efficiency does not degrade as fast as for lower-band-gap semiconductors, such as silicon, so they can be used at high concentration factors.⁹ In addition, GaAs cells are more resistant to radiation damage than silicon cells,¹⁰ thus promising a longer life as well as higher performance in the space environment.

The commercial viability of GaAs solar cells has not yet been demonstrated on a scale which even remotely approaches the SSP requirements. Most work has been done on solar cells produced under laboratory conditions. Pilot plant production still remains to be demonstrated for particular fabrication processes; thus, projections of costs to achieve the large-area solar cell arrays for the SSP must be considered speculative.

The following are processes which are being developed to produce high-efficiency and large-area GaAs solar cells

1. Liquid-Phase Epitaxy

In this process, a 900°C melt of gallium saturated with GaAs is brought in contact with a GaAs substrate and cooled over a specified temperature range. The solution of GaAs, dissolved in pure gallium, is doped with tin, silicon or germanium.

A second melt containing Ga and Al is used in the formation of heterojunction cells. The first epitaxial layer is grown by allowing contact between the GaAs substrate and the first melt (Ga(GaAs)). The junction is formed by allowing contact between this first layer and the second melt (GaAl).

The components in these systems have low vapor pressures to insure homogeneity and long-term reproducibility of the growth matrix. The solutions are always kept saturated at the growth temperature, allowing successive layers to be grown with a minimum growth-cycle time (Figure 4).¹¹ The price of the GaAs solar cell is comparable to the present price of space-qualified silicon solar cell, about \$5 for a 4-cm² solar cell.

2. Vapor-Phase Epitaxy

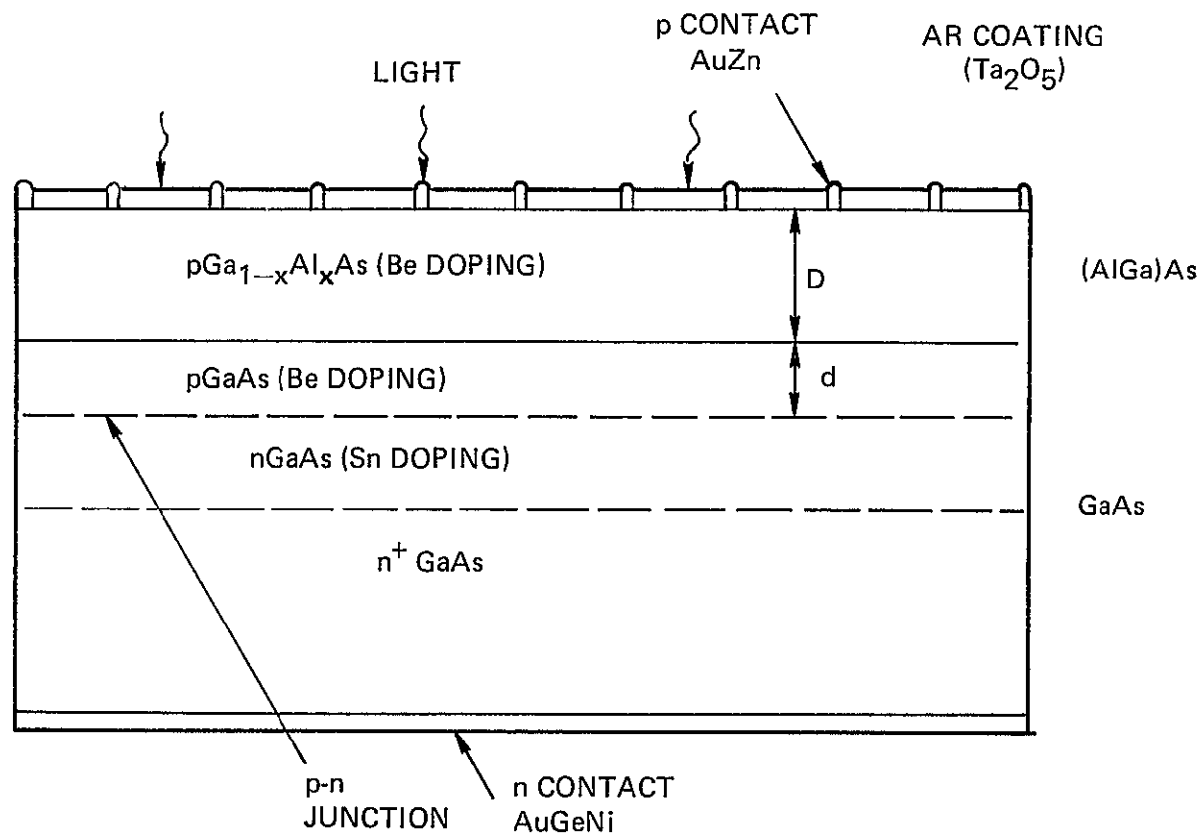
In this process, a junction-forming layer of n-AlAs is grown by chloride-transport vapor-phase epitaxy (VPE) directly on a p-GaAs single-crystal substrate. The VPE process¹² does not require any gallium beyond that in the substrate, and it could be scaled to production rates of about 1000 m² per year. Performance of this single-crystal solar cell material is equivalent to that reported for the liquid-phase epitaxial heterojunction cells.

Instead of the 400- μ m-thick GaAs single-crystal substrate, graphite substrates could be utilized to grow polycrystalline GaAs cells. These solar cells show promise of having good junction characteristics and very good quantum efficiencies.¹²

3. Peeled-Film Technology

This process is designed to produce films 20 μ m thick.¹³ The solar cell and a Ga_{1-x}Al_xAs intermediate layer are grown by liquid-phase epitaxy on a GaAs substrate. The intermediate layer is etched away with HF for approximately 3 hours to produce a thin film. Solar cells with up to 13% efficiency have been produced. Although this method is interesting, considerable development will be required to reduce the material thickness of the solar cell and to speed up the process. One possibility being investigated is to peel numerous GaAs thin films from the (GaAl)As/GaAs alternatively grown multi-layered structure. In this process (GaAl)As and GaAs are grown alternately on a GaAs substrate to a buildup of many layers. The stack is then bathed with HF so that the (GaAl)As layers are dissolved, leaving the 20- μ m-thick GaAs layers intact.

All these processes, although producing GaAs cells of impressive efficiencies, are not yet capable of achieving large production volumes. Thus, a major effort will be required to evolve processes with increased production rates so that they can be considered for SSP solar cell array applications.



Typical Parameters

$n = 5 \cdot 10^{16} \text{ cm}^{-3}$ $D = 0.5 \mu\text{m}$
 $p = 5 \cdot 10^{18} \text{ cm}^{-3}$ $d = < 1 \mu\text{m}$
 $x = 0.97$
 Area = 4 cm^2
 Coverglass: $300 \mu\text{m}$ Thick

Source: Reference 11.

FIGURE 4 GaAs SOLAR CELL

D. CADMIUM SULFIDE

There has been a major advance in the basic understanding of the parameters affecting the performance of CdS solar cells;¹⁴ conversion efficiencies of up to 8.2% have been recently demonstrated. A significant advance in the development of ZnCdS films for use in heterojunction solar cells has resulted in a substantial increase in the open circuit voltage (to 0.7V) but lower current collection effectiveness.¹⁵ The improved performance of the Cu₂S/ZnCdS heterojunction solar cells appears to be due to a better lattice match and the electron affinity between the zinc, the cadmium sulfide, and the copper sulfide. However, improved infrared current collection must be obtained to achieve the projected 15% efficiency. Cadmium sulfide solar cells are of substantial interest because.

- Substantial advances in solar cell efficiencies have been achieved (Figure 5),
- Thicknesses between 5 and 10 μm are adequate;
- The deposition of the materials on inexpensive plastic or glass substrates can be achieved by processes which lend themselves to mass production; and
- Utilizing technology which has been developed for commercial thin film materials, a high degree of automation is possible.

The following two processes show considerable promise:

1. Vacuum Deposition

In this process, cadmium sulfide and other required components are vacuum vapor-deposited on to prepared plastic substrates such as Kapton. Pilot-plant quantities of solar cells have been produced. Clevite Corporation developed cadmium sulfide cells a decade ago for use in space. More recent advances by the University of Delaware indicate their potential for SSP applications. Economic analyses of this process indicate that with mass production, costs should be in the range of 10-20¢ per watt.

2. Chemical Spray Deposition

An alternative technique, developed by Photon Power Corporation, is to deposit the cadmium sulfide and copper sulfide layers by a chemical-spray technique on to a hot substrate (Figure 6). A third layer, tin oxide, acts as a negative electrode. Solar radiation first passes through the glass substrate and then into the solar cell material. This spray process can take place at atmospheric pressure and could be integrated with a float-glass plant to achieve large-scale production. Solar cells produced by the chemical spray technique have achieved efficiency levels of about 5%. Analysis of the loss mechanism shows that efficiency levels could approach 10%. Cost projections indicate that with mass production, the solar cell costs could be about 10¢ per watt.

Although as presently conceived the chemical spray process would not be appropriate for SSP solar cells, primarily because of the substantial glass thickness required for the substrate, it is an interesting process which conceivably could be developed to meet SSP requirements.

AM 1
23°C

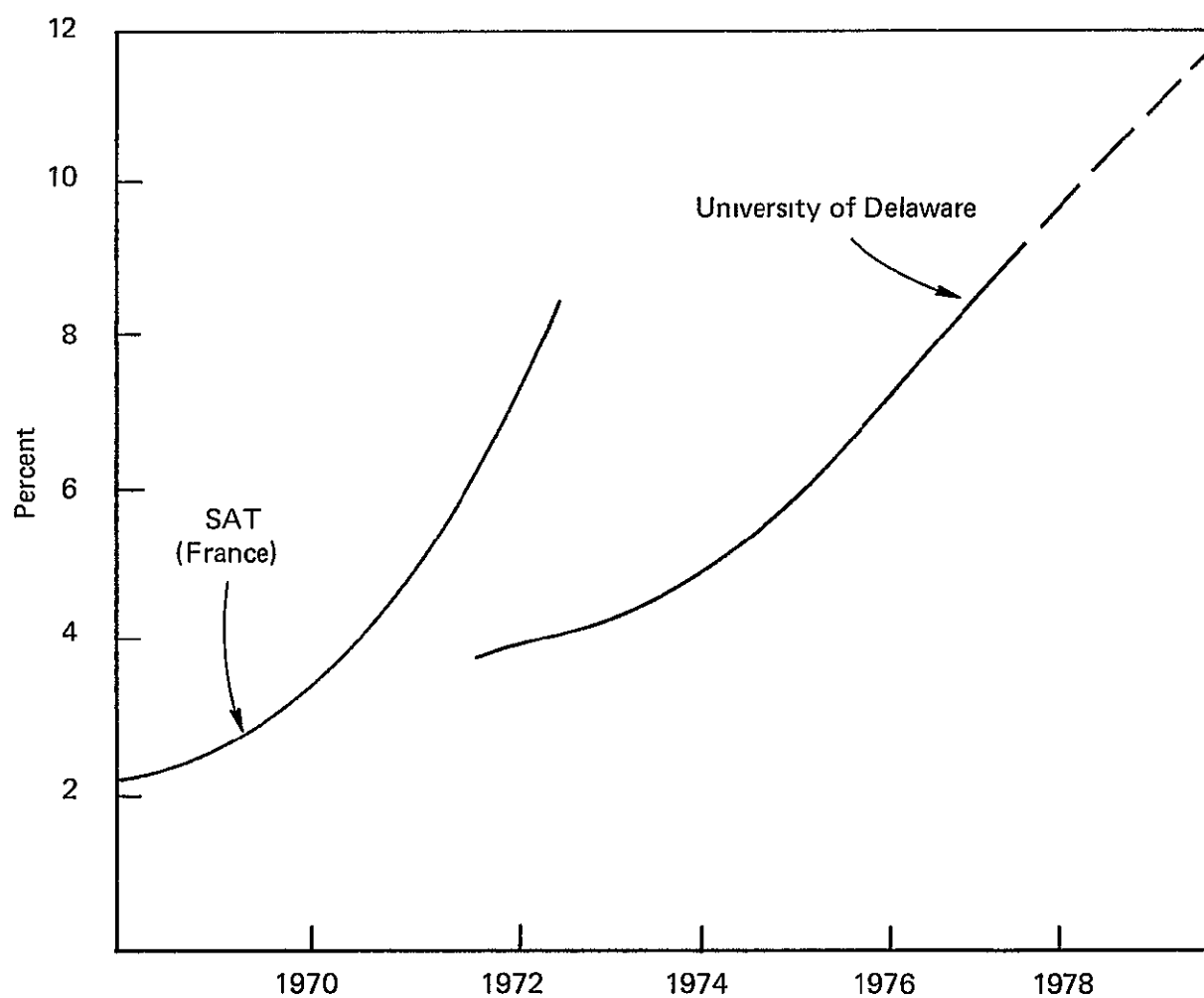
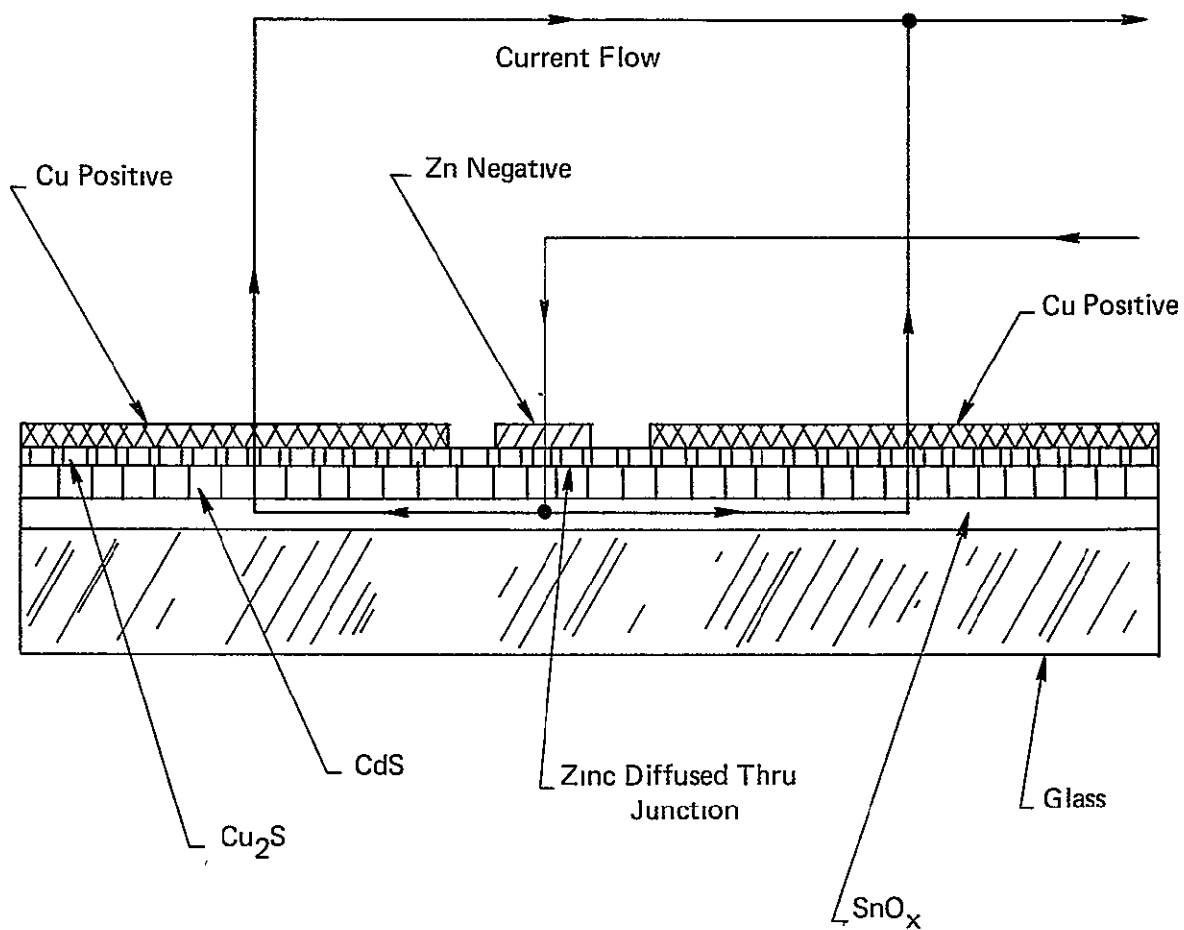


FIGURE 5 HISTORICAL AND PROJECTED CdS THIN-FILM EFFICIENCY IMPROVEMENT



Source: Reference 16.

FIGURE 6 CdS SOLAR CELL PRODUCED BY CHEMICAL SPRAY TECHNIQUE

Neither the vacuum-deposition nor the chemical spray process to produce cadmium sulfide solar cells constrain the cell size. For example, solar cells 20 cm² could be developed, thereby reducing the number of solar cell interconnects.

E. IMPLICATIONS OF LARGE PRODUCTION VOLUMES

Having to meet the requirement for achieving mass production volumes will impose a constraint on several of the solar cell fabrication processes now under development. Assuming that a 5,000-megawatt SSP will require 8,620 megawatts to be generated by the solar array, that the DC-to-DC conversion efficiency will be 58% and that the solar cells will be used without concentration at a solar constant of 1,353 W/m², the required SSP solar cell areas will depend on the efficiency of the cells used (Table 6) (Solar concentrators would reduce these cell areas.)

TABLE 6
SOLAR CELL ARRAY PRODUCTION RATE REQUIREMENTS

Note: Assumptions

Manufacturing operations, with no down time, 24 hours/day,
365 days/year, and 100% yield.

Cell Efficiency	Hourly Production Rate (m ² /hr)		
	1 SSP/Year	3 SSP/Year	6 SSP/Year
10%	7,270	21,815	43,630
15%	4,847	14,543	29,087
20%	3,635	10,908	21,815

Assuming 3 SSP's are to be placed in operation per year with a solar cell efficiency of 15%, a production rate of about 15,000 m²/hr, about the present rate of production of a comparable surface area of automobile tires, is indicative of the size of production scale-up required. For example, if this production rate is to be met by an EFG silicon 75-cm-wide ribbon being grown at the rate of 7.5 cm/min, about 43,000 ribbons would have to be grown simultaneously and integrated with the solar cell array production line. Although this is a large production requirement, machines producing multiple ribbons could be designed and the production shared among a number of factories, as is the case with other mass-produced items, such as tires, refrigerators, TV's, etc.

As shown by the required linear manufacturing rate of solar cell arrays associated with construction scenarios for the SSP for three cell efficiencies and for a number of assumed total solar array widths (Tables 7 and 8), a time-consuming process step will translate into a larger linear dimension needed to complete that process step.

TABLE 7
REQUIRED LINEAR MANUFACTURING RATES OF
SOLAR CELL ARRAY

Total Array Width (m)	Cell Efficiency (%)	Linear Manufacturing Rate (cm/sec)		
		SSP/Year		
		1	3	6
10	10	20.2	60.6	121.2
	15	13.5	40.4	87.5
	20	10.1	30.3	60.6
100	10	2.0	6.1	12.1
	15	1.4	4.0	8.8
	20	1.0	3.0	6.1
1000	10	0.2	0.6	1.2
	15	0.14	0.4	0.9
	20	0.1	0.3	0.6

TABLE 8
SSP AREA REQUIRED FOR SPECIFIC
SOLAR CELL EFFICIENCY
Note: Concentration ratio of 1.0, $S = 1353 \text{ W/m}^2$

Solar Cell Efficiency	SSP Area (km^2)
10%	63.7
15%	42.5
20%	31.9

V. HIGH-VOLUME MANUFACTURE OF SOLAR CELLS

A. CELL PARAMETERS

1. High Yield

The manufacturing objective must be to avoid material losses during fabrication, for example, by minimizing saw kerf losses, which may range from 30 to 50 percent, and end and edge losses for single-crystal silicon ingots. Experience indicates that up to 30% of the modules being produced require some form of rework. Single-crystal silicon solar cells 30 to 50 μm thick should have only a minimum of material removed by surface-etching techniques. A low failure rate of solar cell interconnections during assembly will be essential to obtain acceptable modules.

2. Uniformity of Cells

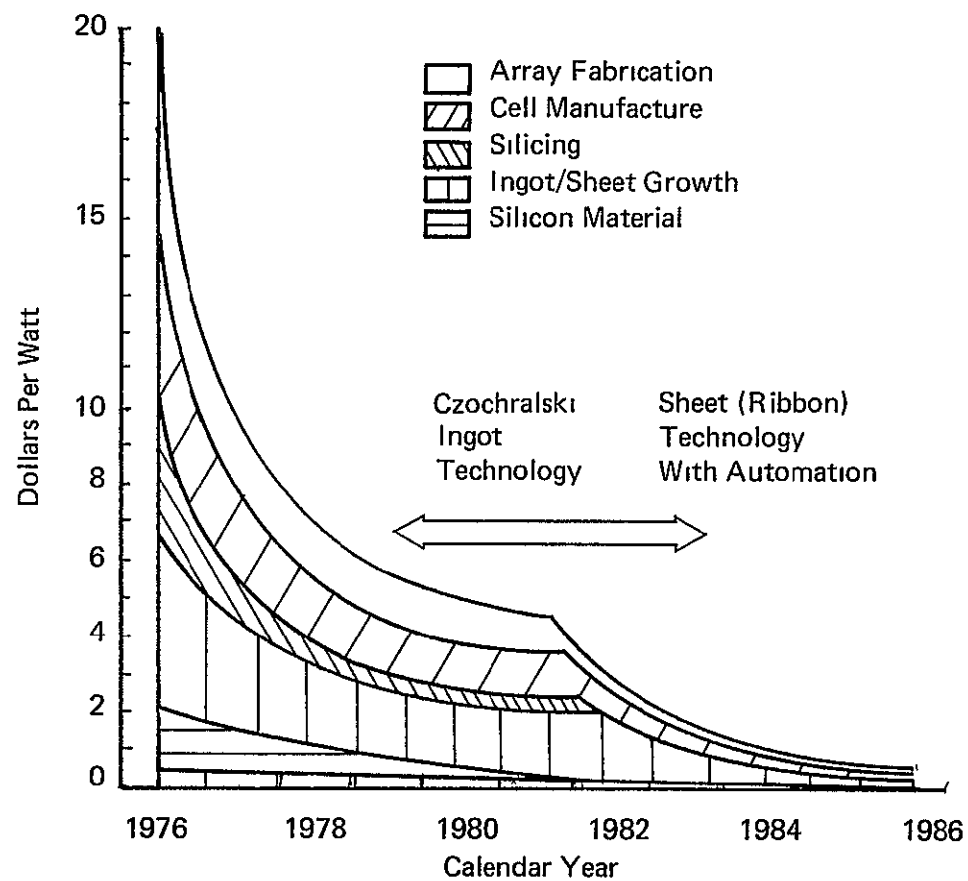
To obtain high efficiency, the production process must control the following parameters: electron mobility, resistive losses, transmittance losses, dopant distribution, metallization patterns, plating of contacts, and antireflection coatings.

3. Low Energy Consumption

To reduce energy consumption during the solar cell manufacturing process, repeated temperature cycling of the material going through the various process steps should be eliminated and the mass of material to be heated minimized. For example, with current technology for silicon solar cells the energy payback time is 12 years for use in terrestrial applications. Improving silicon ingot sawing technology from the present capability of 300- μm slice thickness and kerf loss to 100 μm would reduce the terrestrial solar cell payback time to three years.¹⁷ Replacement of the semiconductor-grade silicon process with a solar-grade silicon process could reduce energy payback time for terrestrial solar cells to 12 months for the 300- μm thickness, and to 4 months for the 100- μm thickness.¹⁸ Similar technology developments will also improve the energy payback period for silicon solar cells to be used in space. The substantial reduction in energy requirement of the present semiconductor-grade silicon is obvious when comparing the energy requirements with those of other common metals (Table 9)

In view of the requirement for volume production, considerable efforts can be expended to automate the processes and to control them to the degree necessary to achieve acceptable uniformity in the solar cell array parameters. The large production volumes will make sophisticated process controls and in-process testing of solar cell parameters economically feasible.

The schedule for the low-cost silicon solar array project calls for initiation and construction of experimental plants by 1980, at which time the scale up from small, single-crystal batch processes to automated processes will have been completed (Figure 7). This implies that the costs will have been reduced by a factor of 30, energy



Source: Reference 4.

FIGURE 7 TERRESTRIAL SOLAR ARRAY PRICE GOALS

requirements optimized and process yields substantially improved to approach the desired production rates of the solar cell arrays. The SSP requirement of low mass per unit area, low cost per watt per unit area, and use of materials which are more radiation resistant than single-crystal silicon solar cells could introduce additional process uncertainties, as the sheet processes developed for terrestrial solar cell production may not meet SSP requirements. To reduce the uncertainties and to meet SSP development schedules, it will be necessary to increase the production volume and market penetration of appropriate solar cells, develop continuous processes, automated production capacities, and demonstrate solar cell arrays in pilot and prototype SSP's.

TABLE 9
COMPARISON OF TOTAL ENERGY REQUIREMENTS TO
PRODUCE SILICON AND OTHER COMMON METALS

Metal	Equivalent Energy [kWh(e)/kg]
SeG-Si	620
Ti	46
Mg	33
MG-Si	24
Al	19
Cu	5
Fe	2

MG = metallurgical grade
SeG = semiconductor grade
(e) = electrical energy

Source: Reference 18.

4. High Packing Factor

Solar cells with either a square or a rectangular geometry can achieve high packing factors. A large individual solar cell size will minimize the number of electrical interconnections, thereby reducing the possibility for failure of individual cells. Polycrystalline solar cells could be produced in larger sizes than single-crystal solar cells

B. MANUFACTURING UNCERTAINTIES

Low-cost processes capable of high-volume production of solar cell materials have yet to be demonstrated. In addition to cost, the following uncertainties also will have to be overcome to produce high-performance solar cells.

- *Purity of the raw materials* used for the production of single crystal and polycrystalline solar cell materials;
- *Control of fabrication steps* to achieve uniform temperatures over extended areas and uniform pressures of gas densities over extended volumes;
- *Cleanliness* to avoid self-contamination between fabrication steps;
- *Surface effects* induced by multiple-wire or blade sawing processes;
- *Metallization methods* to reduce metal line widths; and
- Possible use of *base metals* for interconnects to reduce cost.

C. COSTS

1. Projection Methods

One of the major uncertainties facing the production of extremely large volumes of solar cell arrays which will be necessary to meet SSP projected deployment schedules is their ultimate cost. Of the several methods that can be used to predict future costs (and selling prices) of solar cell arrays, the method which is being used most widely is extrapolation of past experience in achieving production volumes. This approach is applicable to silicon solar cells, since they have already reached an advanced state of development and are gaining market acceptance. Also useful are design-to-cost projections. These are based primarily on engineering judgment and are useful to allocate production cost goals to individual elements of the production process.

a. *Historical Production Volumes and Cost Projections*

A common experience in the marketplace is for the price of a new product to decline after its initial introduction as it becomes more widely known and commonly available. It has also been recognized that the price declines show a remarkably consistent pattern — one that appears to apply to a wide range of products. In the characteristic pattern, the price declines by a constant percentage with each doubling of the total number of units produced by an entire industry sector.

The price decline and the hours of labor required to produce a product can be described in terms of a “learning curve”¹⁹ If prices decline according to a set pattern, then the costs of successful producers must behave similarly. They must decline enough to stay below the prices. Rapidly declining costs accompanied by steadily increasing profits attract more competition and industry capacity and thus pressure for further price reductions. The key phenomenon is the reduction of unit costs made possible by increased experience. The characteristic decline is consistently 20 to 30 percent each time accumulated production is doubled — and the rate of decline is consistent even from industry to industry.²⁰ This decline continues without limit (in constant dollars) regardless of the rate of growth of experience. If the production of a product is not increasing, then the rate of cost decline per year gradually slows down to zero.

Industry data provide remarkably consistent evidence of cost-volume relationships based on a combination of factors, such as learning effects, scale effects, cost rationalization and technology. Cost reductions as a result of increasing volume

attributable to learning permit the use of more efficient tools and spread the cost over enough units so that labor and overhead costs are reduced. With increased scale, it is possible to tailor facility-use factors more closely to capacity. With increasing volume, alternative materials, methods of manufacture, and distribution can be considered which would be uneconomic on a small scale. These can lead to cost rationalization. Successful redesign of a product usually reduces the unit cost substantially as long as the anticipated volume is adequate to spread the cost of the redesign. Advanced technology resulting from R&D will reduce costs but the potential application of R&D to cost reduction is a direct function of the volume to which its results can be applied.

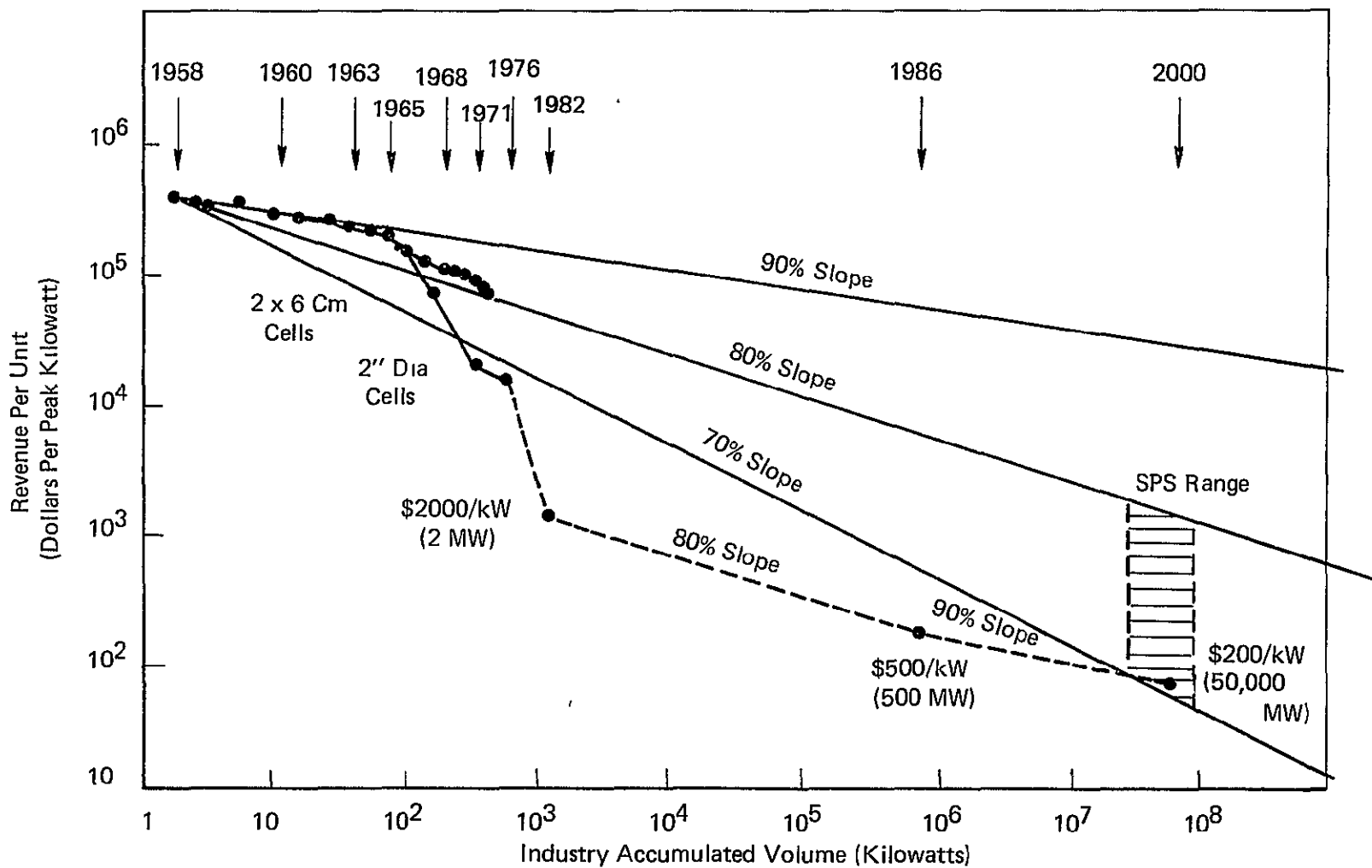
This pattern, also applicable to projecting costs of terrestrial silicon solar cells (Figure 8), indicates that the rapid growth rate projected for silicon solar cells will justify near-term investments in order to obtain and accumulate experience.

The major growth characteristics projected for the silicon solar cell market for terrestrial applications also justify this method of cost projection. Although at first the market is expected to be stimulated primarily by government purchases, expected commercialization of the technologies within the foreseeable future is expected to lead to further market growth, and thus to increased industry-accumulated volume and further cost reductions.

The experience curves would not apply if major elements of cost or price are determined by patent monopolies, material supply, or government regulations. These factors are unlikely to apply to silicon, but because of their more limited availability compared to silicon, cadmium sulfide and gallium arsenide introduce uncertainties, particularly at greatly increased volume.

Experience curve projections are useful where marketing data for a number of years are available and where the growth of the market will not be strongly influenced by one application. The substantial impact on industry-accumulated volume represented by just one SSP means that the experience curve projection must be used with caution. For example, the assumption that there is a steadily growing market and that industry has an opportunity to make capital investments which can be amortized over a reasonable time span introduces uncertainties when the major market for solar cells is the SSP. Major capital investments will be required for SSP demonstrations and profitable markets for the output will have to be found, particularly if the SSP requirements for solar cell arrays are intermittent. Once a commitment to commercialize the SSP is made, the production volume can be adjusted to meet SSP deployment schedules. However, prior to this commitment to meet the SSP prototype requirements, substantial production volume will be required without an assured future market. Thus manufacturers will have to find intermediate markets.

As the integrated production volume leading up to the commercial production of the SSP will be very substantial, it may be necessary to design solar cells capable of satisfying both SSP and terrestrial applications. Should it be possible to evolve a solar cell design which could meet both, then it would be easier for industry to make substantial capital investments if near-term markets are identified. This approach would also reduce the funding pressures on the SSP development program. Therefore,



Source: Reference 4.

FIGURE 8 REDUCTION PROJECTIONS BASED ON INDUSTRY EXPERIENCE

rather than seeking ways to modify terrestrial solar cells to meet SSP requirements, there may be an advantage in designing solar cell arrays and appropriate production methods which would meet the more stringent SSP requirements and also meet the needs of terrestrial applications. This implies planning for potential technology transfer opportunities at an early stage of the SSP development program.

b Allocation of Costs to Production Process Elements

In this approach, portions of the total cost of producing solar cells are allocated to the various process elements so that each process element can be tested against its individual cost goal. This permits key cost barriers to be identified and evaluated to point the way to required technical innovations to achieve desired cost reductions. The allocation of the total cost of the individual process elements relies primarily on engineering judgment and is influenced by factors known to the experienced designers and engineers. For single-crystal silicon solar cell efficiencies in the range from 15 to 18%, the following design-to-cost allocations are projected.

	$\$/\text{m}^2$ Range
Single-Crystal Silicon	25 to 35
Junction Formation	10 to 15
Metallization	5 to 15
Anti-reflection	5 to 10
Array Assembly	15 to 30
	60 to 105

The cost per watt is a function of solar cell efficiency, the solar flux, and the cost per unit area. For example, a cost goal of 50¢ per watt at 15% efficiency (AMO) translates into \$100 per m^2 ; 30¢ per watt at 15%, into \$60 per m^2 . An 18%-efficient cell could be allocated \$120 per m^2 to achieve a cost goal of 50¢ per watt; and \$72 per m^2 , for 30¢ per watt.

The ERDA/JPL low-cost silicon solar array project will test how close design-to-cost goals can be met. Although the companies involved in this project (Texas Instruments, Motorola, and RCA) are reasonably confident, based on detailed cost calculations for the individual process elements, that the design-to-cost goals can be met, significant production volumes will be required to demonstrate it. This is being done in part through increasingly larger ERDA purchases of silicon solar cell arrays which are being used for various demonstration projects. Although the scale of these purchases (40 kW in 1976 and 130 kW in 1977) is modest, continued market growth will indicate whether the design-to-cost goals are being met.

2. Solar Cell Cost Projections

There are uncertainties in the cost projections associated with solar cell production volumes required to meet projected ERDA objectives and SSP requirements. The work being undertaken under the National Photovoltaic Conversion program is providing the information required to reduce these uncertainties. Available published data and discussions with photovoltaic specialists indicate that the cost ranges for single-crystal silicon solar cells applicable to the SSP are 50 to 70¢ per watt by 1985, and 15 to 25¢ per watt by 1995.

Cost projections for thin-film solar cells, which are at an earlier stage of development and therefore are more uncertain, indicate the following ranges:

- Amorphous Silicon: 15 to 30¢ per watt by 1987,
- Cadmium Sulfide: 10 to 20¢ per watt by 1985, and
- Gallium Arsenide: ~ \$1.00 per watt

Gallium arsenide production processes are in too early a stage of development to permit appropriate cost goals to be established. However, successful demonstration of gallium arsenide solar cells at concentration factors in the range of 4 to 7 could permit the use of more expensive gallium arsenide solar cells if the cost of the optical concentration system could be kept low: at high concentration factors the importance of the cost of the solar cells declines if the cell efficiency is high. For this reason discrete-band-gap solar cells,²⁶ which are projected to approach efficiencies greater than 30%, may be cost effective even though they are expensive

In view of the dynamic growth of the photovoltaic materials field, it is not unreasonable to expect the significant advances which recently have characterized this field to continue. Therefore, novel photovoltaic material combinations, improved solar cell designs, and automated production processes hold promise for approaching the cost goals for the SSP.

VI. EFFECTS OF CONCENTRATION RATIO

The primary purpose of considering optical concentration of sunlight for the SSP is to reduce the area of solar cells required to generate a fixed level of power. A reduction in total array area required per satellite reduces the annual solar array production levels needed to support the SSP program, thereby reducing the demand on natural resources that may be difficult to obtain. The added mass plus additional fabrication and assembly complexities of augmented* cooling for the array have led to consideration of only passive cooling of the cells, using a heat-rejection area equal to the area actually covered by the solar cells. Therefore, at higher levels of concentration, the temperature of the individual solar cells increases and their conversion efficiency decreases, even though more watts per unit area are being generated because of the higher intensity of incident sunlight. A minimum in the curve of required solar array area plotted against concentration ratio occurs when, for an increase in concentration ratio the further decrease in cell efficiency (due to its increasing temperature) offsets the increase in intensity of incident sunlight, so that the solar cell generates a lower power per unit area.

As the concentration ratio is increased, with a passively cooled cell, the decrease in cell conversion efficiency requires a larger area of sunlight to be intercepted by the total SSP and, therefore, the overall projected area of the reflectors and array must increase.

The Arthur D Little deterministic computer model²¹ of the solar energy conversion subsystem was exercised to determine the variation in array mass (area) with concentration ratio for a fixed electrical power output. Solar array and total SSP mass were compared for three candidate materials (silicon, cadmium sulfide and gallium arsenide), assuming passive cooling from the front and back surfaces of the array only. Emerging cell efficiencies were considered for each candidate material (silicon -16%, cadmium sulfide -10%, gallium arsenide -18%, at AMO are 26°C).

Additional assumptions inherent in the deterministic analyses of the photovoltaic conversion subsystem of the SSP are as follows:

• Solar Constant	1353 W/m ²
• Power Developed by Photovoltaics	9.141 x 10 ⁸ kW
• Mass/Unit Area Support Structure	21,300 kg/km ²
• Cost \$/Unit Mass Support Structure	\$81/kg
• Mass/Unit Area Reflectors	29,670 kg/km ²
• Cost \$/Unit Area Reflectors	\$1.035 x 10 ⁶ /km ²
• Transportation Costs to GEO	\$80/kg

The array mass (area) using silicon cells ($\eta = 16\%$) is a minimum at a concentration ratio of 2.4 (Figure 9), however, the total mass of the SSP as a function of concentration ratio is monotonically increasing.

*Augmented cooling refers to a heat-rejection radiating area for the solar cell arrays that is larger than the area actually covered by the solar cells but thermally well-coupled to the solar cell area.

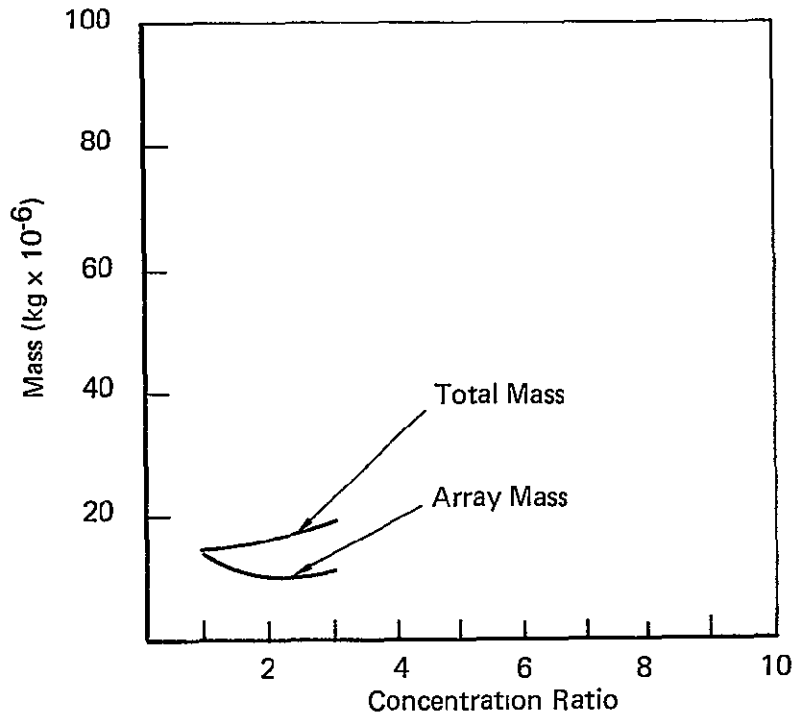


FIGURE 9 VARIATION IN ARRAY MASS OF SSP AS A FUNCTION OF CONCENTRATION RATIO — SILICON

The array mass using cadmium sulfide ($\eta = 10\%$) is a minimum at a concentration ratio of 2.8 (Figure 10). The total mass, however, is again an increasing function of concentration ratio.

The array mass using gallium arsenide ($\eta = 18\%$) decreases with concentration ratio (Figure 11), but the total mass exhibits a minimum. To minimize the total mass of a gallium arsenide SSP, a concentration ratio of about 4 should be used.

The determination of an "optimum" concentration ratio for the SSP requires a consideration of a great many other factors than are discussed here; and the choice of a final design basically depends on system economics. The primary purpose of this discussion is to show that the choice of concentration ratio for the orbiting power station has an impact on the required annual production levels of the SSP solar arrays. Solar concentration would favor those photovoltaic materials whose availability is limited, e.g., gallium. A comparison of solar cell array area per satellite between a design that incorporates no concentration and a design that minimizes the solar cell area for a passively cooled system would be as follows:

Solar Cell		Concentration Ratio	Solar Cell Array Area Per Satellite (km ²)
Material	Efficiency* (%)		
Silicon	16	1.0	49.2
		2.4	36.8
Gallium Arsenide	18	1.0	36.1
		>8.0	< 7.1
Cadmium Sulfide	10	1.0	69.8
		2.8	49.2

*Efficiencies shown are for AMO at 26°C.

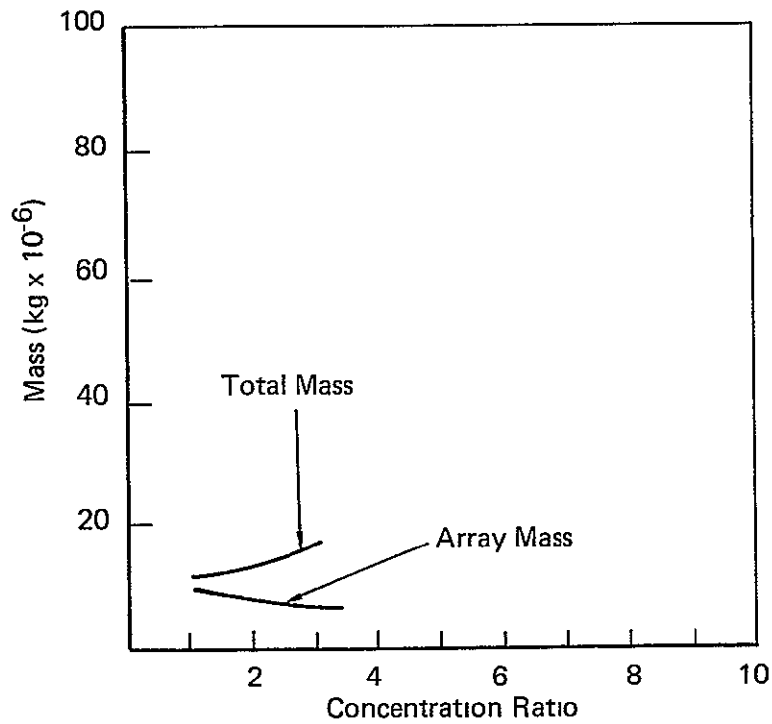


FIGURE 10 VARIATION IN ARRAY MASS OF SSP AS A FUNCTION OF CONCENTRATION RATIO — CADMIUM SULFIDE

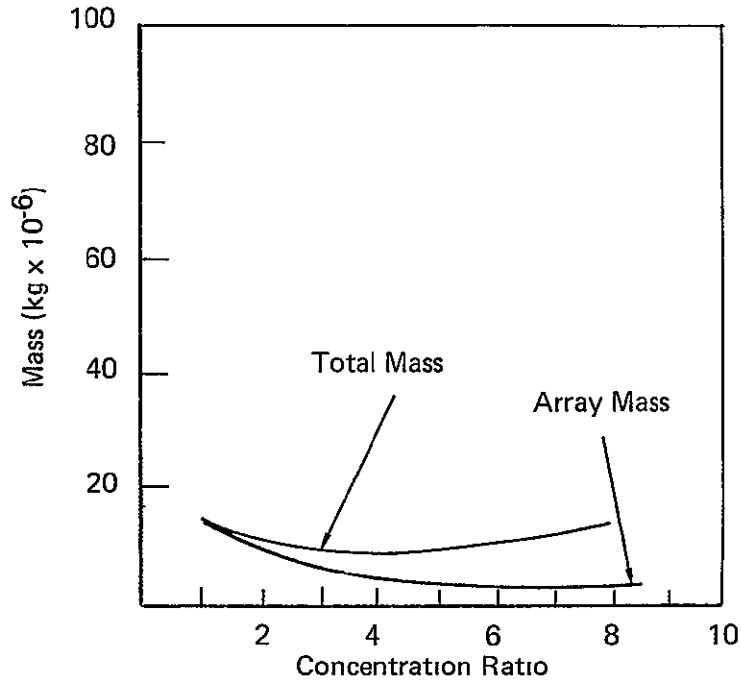


FIGURE 11 VARIATION IN ARRAY MASS OF SSP AS A FUNCTION OF CONCENTRATION RATIO – GALLIUM ARSENIDE

Additional considerations for the analyses of concentration of sunlight for the SSP photovoltaic energy conversion subsystem are the degradation mechanisms that may occur in specific cells if operated at an elevated temperature and the annealing of radiation damage in other cells that may be enhanced at elevated temperatures. The operating temperature of a solar cell as a function of the concentration ratio of normally incident sunlight, assuming a passively cooled cell with a fixed conversion efficiency of 10% at all temperatures, is as follows:

Concentration Ratio	Cell Operating Temperature* (°C)
1.0	51
2.0	112
3.0	154
4.0	185
5.0	212
6.0	234
7.0	254
8.0	272

*10% conversion efficiency assumed at all temperature levels

The solar absorptance of the cell is assumed to be 0.85; its IR emittance, 0.80. The IR emittance of the backside of the array substrate is assumed to be 0.90.

If an illuminated cadmium sulfide cell has stability problems above 60°C in vacuum, then concentration ratios near 1.0 would be needed for an SSP utilizing cadmium sulfide solar cells. A typical Si cell-annealing temperature of 450°C would be outside the range of the indicated cell operating temperatures.

When GaAs solar cells are used at high concentrations, the solar reflector material should have a high UV reflectance. Silver-coated reflecting surfaces are preferable to aluminum in this property.

VII. EFFECTS OF SPACE ENVIRONMENT

The near-Earth radiation environment that is detrimental to solar cell performance consists of electrons and protons trapped in the geomagnetic field (Van Allen belts) and solar flare protons (Table 10). The radiation environment in geosynchronous orbit is dominated by the trapped electrons during periods of normal solar activity and by solar flare protons during maximum solar activity. At lower altitudes, which would be traversed enroute to geosynchronous orbit, significant cell damage may be caused by both types of trapped particles.

TABLE 10
DEFINITION OF REGIONS OF GEOMAGNETICALLY TRAPPED ELECTRONS
AND PROTONS
(VAN ALLEN BELTS)

Zone Definition	Location* (km)			Particle Energy Range (MeV)	
	Minimum Altitude	Maximum Altitude	Peak Intensity	Electrons	Protons
Inner Belt (Hard Belt)	300	6,400	2,900-3,200 above geomagnetic equator	0.020 → 1	< 700
Outer Belt (Soft Belt)	13,000	59,000	16,000-24,000	0.020 → 5	> 60

*Geosynchronous altitude is approximately 35,900 km

Source. Reference 22

Solar flare proton measurements have been made only during the last two solar cycles (Table 11). Most of the solar flare protons that damage solar cells occur in one (or a few) very large flares that seem to occur during a time span of 3 to 4 years centered around the middle of the period of maximum solar activity. In the period of maximum activity of Solar Cycle 20, for example, approximately 5 percent of the total solar flare proton flux occurred in each of the six years from 1966 through 1971, with 70 percent of the total occurring in 1972.

The total radiation environment causes two components to enter the solar cell, one through the coverglass (front) and one through the substrate (back). For the SSP design currently being considered, a lightweight array consisting of the photovoltaic material, coverslide and interconnects being bonded to a lightweight substrate, e.g., Kapton, has a decided advantage due to its low mass and resulting minimum cost to

transport to geosynchronous altitude. Because of the essentially omni-directional characteristic of the trapped electrons and protons, it is important to insure that radiation protection, e.g., a coverslide or substrate material, protect both the front and back side of the array. The mass penalty of a coverslide has to be considered for both sides of the solar cell array. In the ATS-5 solar cell experiment,²³ for example, the lightweight array had a substrate consisting of 1-mil Kapton bonded to 1 mil of 108 fiberglass scrimcloth. The total substrate was equivalent to a 1-mil coverslide. The metallization on the back of the solar cell provided additional protection from the in-orbit radiation environment.

TABLE 11
SUMMARY OF PERIODS OF SOLAR CYCLES

Solar Cycle No.	Period of Cycle	Duration of Maximum Activity
19	1953-1964	1955-1961
20	1964-1975	1966-1972
21	1975-1986	1977-1983
22	1986-1997	1988-1994
23	1997-2008	1999-2005
24	2008-2019	2010-2016
25	2019-2030	2021-2027

Source: Reference 22

A general technique for assessing cell damage is to convert the damage measured or predicted to occur from in-orbit radiation (covering a range of energy levels and particle densities) into damage caused by an equivalent fluence of 1-MeV electrons. Rosenzweig has expressed many of the total fluence calculations for different orbits in equivalent fluence of 1-MeV electrons. For example, a 7-year mission at synchronous altitudes (1970-1977) using 300- μ m (12-mil) Corning 7940 fused-silica coverslides and 300- μ m 10- Ω -cm silicon cells with infinite backshielding had a total calculated equivalent fluence of 3×10^{14} e-cm⁻² of 1-MeV electrons.²⁴

The significance of this radiation-produced cell damage is that a reduction (gradual or precipitous) in cell efficiency reduces the power generated by one (or many) orbiting solar power stations, resulting in a decrease in the revenue which is being generated. Heavier coverslides are a predictable way to increase the radiation resistance of a given cell at the expense of a heavier mass to be transported to geosynchronous altitude and, therefore, a higher initial capital investment.

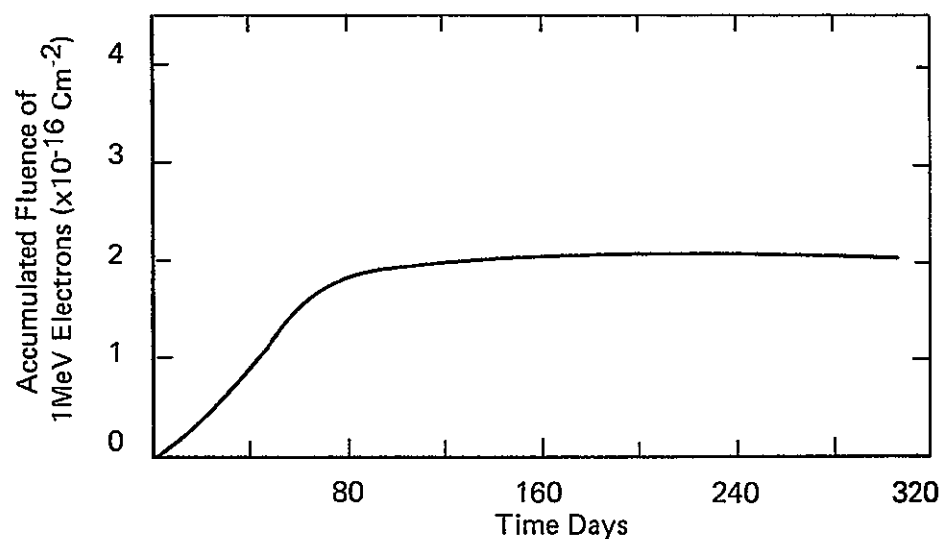
Different cell materials and cell geometries (for example, a vertical junction cell)³ also can provide increased resistance to radiation degradation. Both gallium arsenide and cadmium sulfide heterojunctions have shown better resistance to cell degradation by irradiation than a conventional silicon cell. Recent results by Hughes Research Laboratories⁶ show that a coverglass thickness of approximately 4 mils would be needed to keep a GaAs cell conversion efficiency above 19 percent (initially 20 percent) after being subjected in orbit to high energy solar flare protons for 33 years. It is assumed that this is for front surface protection only.

Measurements²³ have shown no decrease in the conversion efficiency of a CdS cell after exposure to 10^{16} e-cm⁻² of 1-MeV electrons although some damage occurred to the Mylar cover.

Generally a solar cell having a higher resistance to radiation damage will have a lower initial conversion efficiency. The system designer of an SSP is then given the following choice: (1) a power vs. time profile that gradually declines but provides a higher initial conversion efficiency; or (2) a power vs. time profile that is more constant but provides a lower initial conversion efficiency and hence a larger SSP in orbit. This tradeoff points out the obvious benefit of a solar cell that can be annealed in orbit, thereby permitting the high-efficiency cell to be used over a long period of time.

In addition to the radiation resistance required at geosynchronous altitude, additional resistance will be needed during transit through the Van Allen belts to geosynchronous altitude.

A transfer orbit degradation curve was developed by the Charles Stark Draper Laboratory for the SERT-C mission,²⁵ in which the power degradation experienced by the solar array also reduced the electric power available for ion propulsion (Figure 12). For a 10-mil cell with a 6-mil front coverslide and infinite backshielding, the 308-day transfer from an initial altitude of 9528 km at 28.3° to geosynchronous altitude resulted in an equivalent accumulated fluence of 7×10^{16} e-cm⁻² of 1-MeV electrons. Based upon the data²³ for an annual equivalent fluence of approximately 7×10^{14} e-cm⁻² 1-MeV electrons for a silicon cell with a 6-mil coverslide, the accumulated fluence during the transfer orbit is equivalent to 100 years at geosynchronous orbit. A reduction in the damage to the individual cells during the transfer orbit can be achieved by: (1) minimizing the transit time (chemical propulsion); (2) encapsulating most of the array in a protective container during transit; (3) annealing the cells after arrival at geosynchronous altitude; or (4) total or partial fabrication of the cells at geosynchronous altitude. After an assessment of technical feasibility, each of these alternatives would require a system level tradeoff study to assess its economic feasibility.



Note:

- Initial Orbit
 $i = 28.3^\circ$
 Alt = 3157 Km
- Final Orbit
 $i = 0^\circ$
 Alt = 35,733 Km

Source: Reference 25.

**FIGURE 12 RADIATION ENVIRONMENT DURING MINIMUM TIME
 TRANSFER ORBIT FROM LEO TO GEO**

VIII. SPACE MANUFACTURE OF SOLAR CELLS

The space manufacture of solar cells is particularly important if single-crystal silicon should be found to be the optimum material for SSP solar cell arrays. During passage through the Van Allen belts, unprotected single-crystal silicon solar cells could suffer 40% degradation, equivalent to that experienced during exposure of 100 years in geosynchronous orbit.²⁵ There is a possibility that this degradation can be reduced by providing protective covers around the packaged solar cells during transportation to orbit. The tradeoff would be the mass of the protective covers around the packaged solar cells during transportation to orbit. The tradeoff would be the mass of the protective covers and the additional cost of transporting the covers into orbit, particularly if there were no secondary use for them.

An alternative approach would be to produce silicon solar cells in a space manufacturing facility. Two processes are being considered for space manufacture of silicon solar cells. One is the ribbon process based on a levitated and RF-heated ribbon being developed by McDonnell Douglas, the other is the process of vapor deposition of silicon on a suitable substrate in the very high vacuum existing in the wake of a spacecraft in synchronous orbit being developed by GE. Both are still in an early stage of development. In addition, the production of amorphous-silicon solar cells by the glow-discharge technique may be utilized in a space manufacturing facility. The advantages of space manufacture will be reduced if the photovoltaic material is not degraded during transit to synchronous orbit and if high-vacuum and near-zero-g conditions are not important to the cell production processes.

If array assembly is reserved for geosynchronous orbit, there are three options for space and assembly of single-crystal silicon solar arrays for the SSP (Table 12). Option I is the least desirable because of the substantial degradation of the silicon solar cells during passage through the Van Allen belts. Option II, utilizing chemical propulsion, would reduce degradation because of the short time of passage through the Van Allen belts. Similarly, Option III, with shielding of the solar cells, could result in lower degradation.

Another, Option IV, relies on space manufacture of solar cells (Table 13). In this option, most of the components which would not be affected by exposure to the Van Allen belts would be manufactured on Earth, e.g., plastic substrates. Solar cell fabrication equipment would be assembled in orbit and the polycrystalline silicon material transported to orbit to meet SSP deployment requirements. Another possible future option is that silicon might be obtained from lunar surface material if it proves to be technically feasible and economically competitive as an alternative to transporting silicon materials from the Earth.

An important system level trade for Option IV is the relative cost of transporting the cell/array fabrication facility from Earth to the in-orbit location compared to the cost of transporting the photovoltaic material to the fabrication site. Figure 13 compares the projected cost of producing polycrystalline silicon on Earth to the cost of

TABLE 12

OPTIONS I-III FOR FABRICATION AND ASSEMBLY OF SINGLE-CRYSTAL SILICON SOLAR ARRAYS FOR SSP

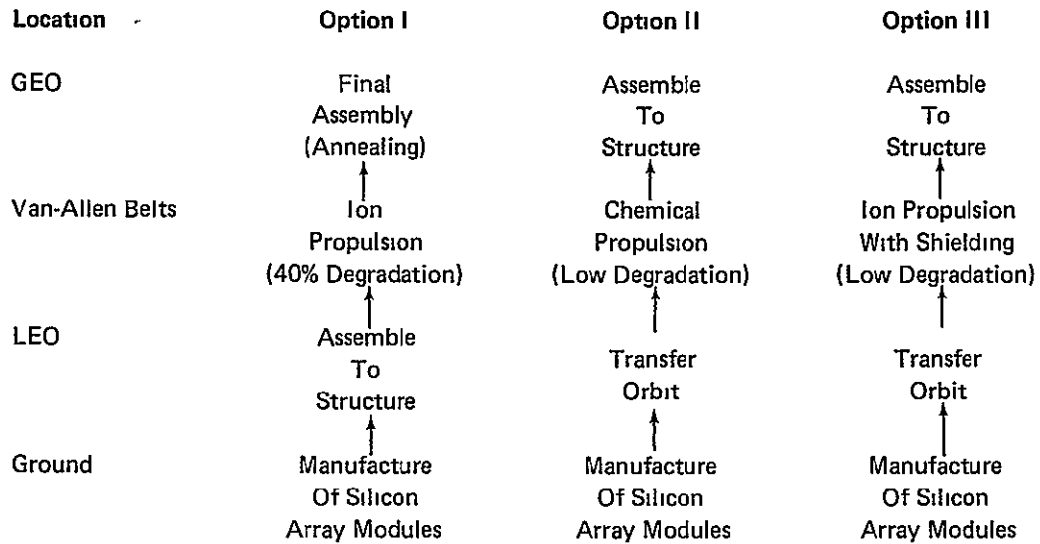
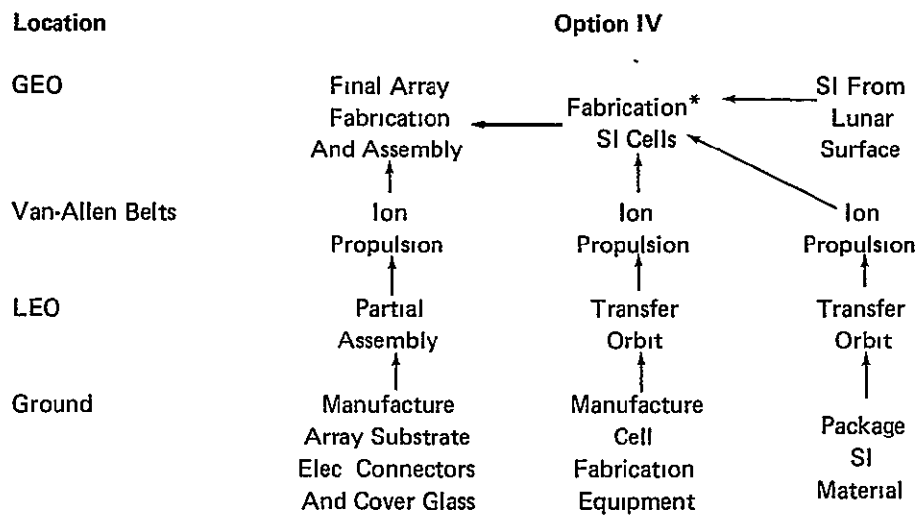
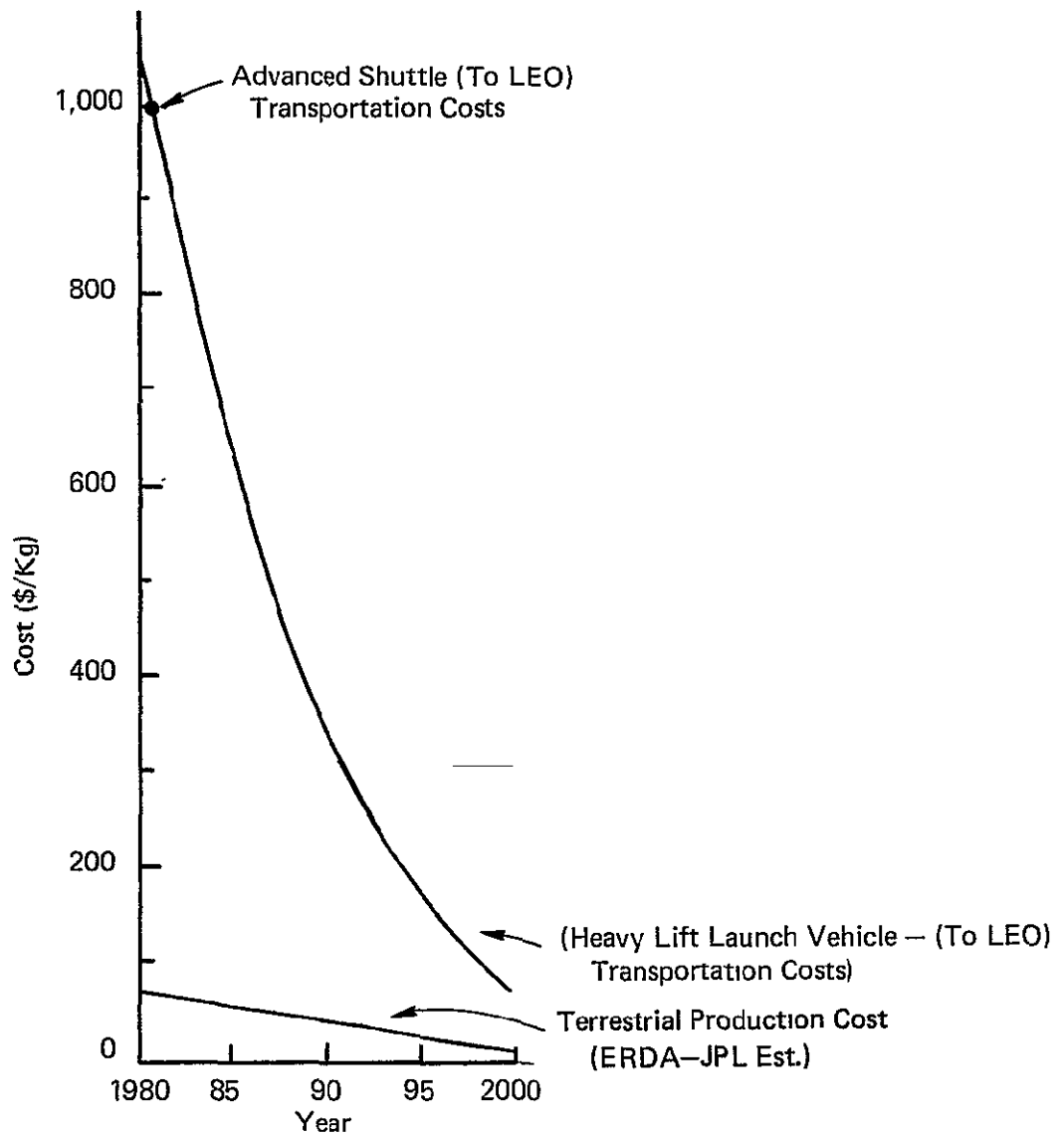


TABLE 13

OPTION IV FOR FABRICATION AND ASSEMBLY OF SINGLE-CRYSTAL SILICON SOLAR ARRAYS FOR SSP



*Cell fabrication site would stay at GEO



Source: Arthur D Little, Inc., estimates.

FIGURE 13 COST OF TRANSPORTING POLYCRYSTALLINE SILICON TO LEO COMPARED WITH TERRESTRIAL PRODUCTION COSTS OF POLYCRYSTALLINE SILICON

transporting the material from Earth to LEO. The high transportation costs, even with HLLV's, favor transporting the minimum amount of mass from the Earth to LEO, i.e., the finished array. If the costs of transporting the photovoltaic material from the lunar surface to the fabrication site are significantly less than the transportation costs from the surface of the Earth, then the costs of transporting the fabrication facility from the surface of the Earth to an in-orbit location would be more attractive. A thin-film solar cell would reduce the mass of photovoltaic material that would be transported to the fabrication site. Therefore, it would be less attractive to orbit the fixed mass of the cell/array fabricator facility

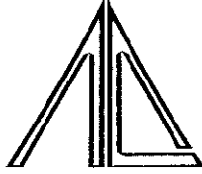
It is less likely that solar cell materials based on cadmium sulfide or gallium arsenide would be produced in a space manufacturing facility because these materials are less affected by the radiation environment in the Van Allen belts

A space manufacturing facility would also permit the recycling of silicon solar cells if annealing procedures fail to restore performance to the desired high level. Recycling of solar cell materials would permit the SSP to be in operation indefinitely.

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